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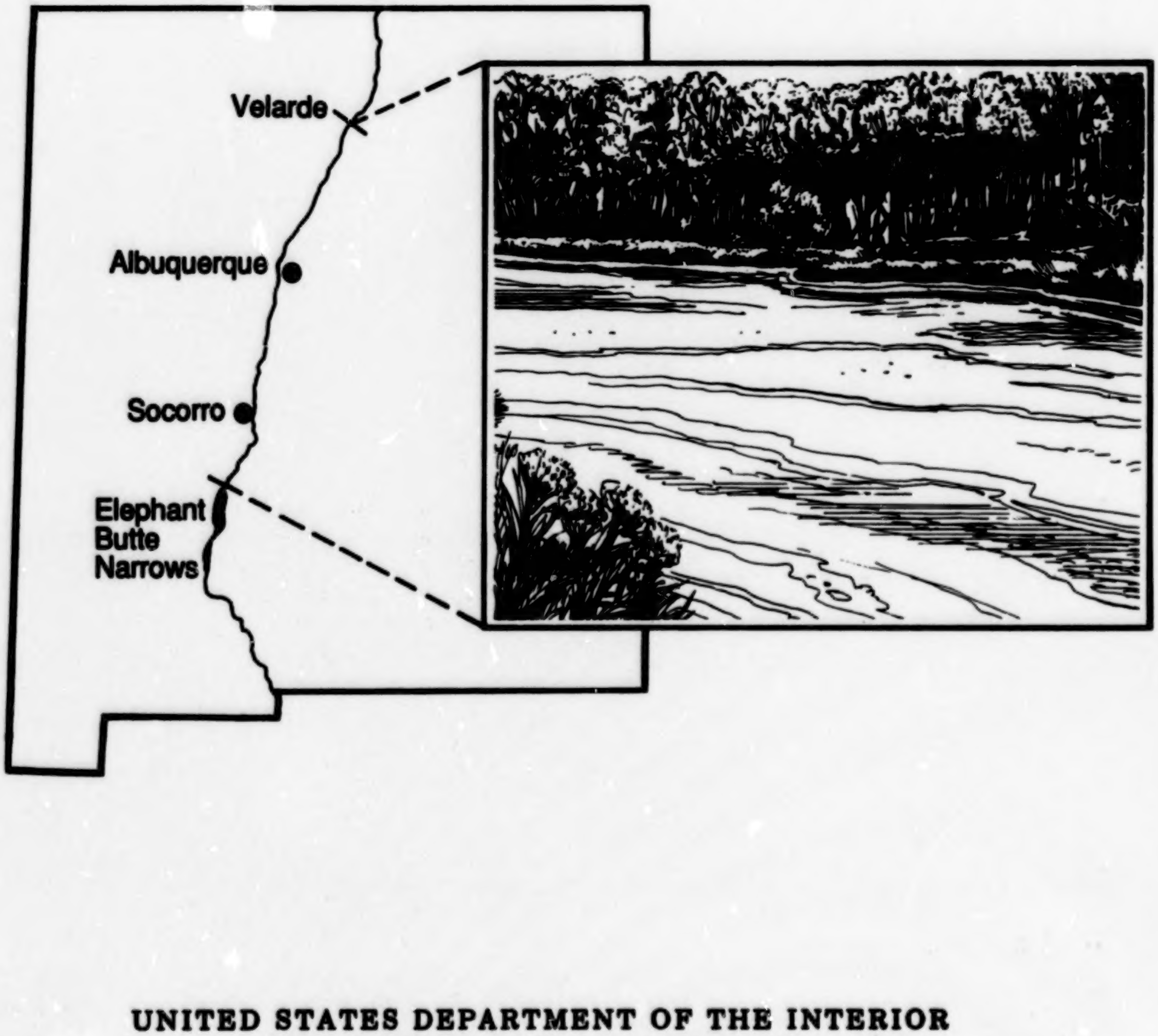
Hydrology of the Middle Rio Grande From Velarde to Elephant Butte Reservoir, New Mexico



UNITED STATES DEPARTMENT OF THE INTERIOR

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Hydrology of the Middle Rio Grande From Velarde to Elephant Butte Reservoir, New Mexico

By Thomas F. Bullard
Stephen G. Wells

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Preface

This report was produced under Purchase Order No. 86117-88-0087 for the U.S. Fish and Wildlife Service's National Ecology Research Center, Fort Collins, Colorado, by the Department of Geology, University of New Mexico, Albuquerque, New Mexico. The purpose of the report is to provide basic hydrologic information and data sources for the Middle Rio Grande, which is defined to be the reach from Velarde to Elephant Butte Reservoir, New Mexico. The report is intended to provide background information for a proposed multi-year research project on the hydrology, vegetation, and wildlife of the Middle Rio Grande. If funded, this project will require substantial data on the past and present hydrology of the Middle Rio Grande for purposes such as identifying potential study sites and understanding the distribution of existing vegetation. If the project is not funded, the report will nonetheless serve as a reference on existing hydrologic information useful to federal, state, university, and other researchers and managers interested in the hydrology and ecology of the Middle Rio Grande.

Hydrology of the Middle Rio Grande From Velarde to Elephant Butte Reservoir, New Mexico

by

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Introduction

The purpose of this report is to provide basic hydrologic information and data sources for the Middle Rio Grande (MRG) as background for a proposed multi-year research project on the hydrology, vegetation, and wildlife of the MRG. The MRG, defined here as the reach from Velarde to Elephant Butte Reservoir, New Mexico, is part of the Rio Grande drainage basin of Colorado, New Mexico, Texas, and Mexico. The Rio Grande drainage basin forms one of the most important international waterways in the United States. The drainage basin is rich in culture and history, as well as controversy over use and management of Rio Grande water.

The Rio Grande basin above El Paso, Texas, is one of the oldest regions of agriculture in the United States. Agricultural activity extends back centuries to prehistoric inhabitants of the Rio Grande valley, and includes the seventeenth and eighteenth century Pueblo Indians and Spanish colonists, and European-Americans in the latter part of the nineteenth century (Wozniak 1987). More recent history of the region involves disputes and concerns over flood management, irrigation, and distribution and delivery of upstream waters to downstream users in an attempt at fair sharing between concerned parties. Because of the long history of agricultural activity, Rio Grande water is tied to public laws governing its conveyance, storage, and use. The close connection between legislation and flow of water through the Rio Grande is largely responsible for the present physical state of the river, floodplain, and associated riparian community. Changes in the floodplain ecology probably began shortly after human settlement in the region, and change has continued relatively unabated with increasing population.

Middle Rio Grande Study Area

Location of the Study Area

The MRG is part of the larger Rio Grande fluvial system (Fig. 1). The Rio Grande headwaters lie along the Continental Divide at elevations ranging from 2,440 to 3,660 m in the San Juan Mountains of southern Colorado. The Rio Grande drains about 3,370 km^2 of these high mountain peaks in the northernmost part of the basin. The entire area of the Rio Grande drainage basin is about 470,000 km^2, of which about 230,000 km^2 are in the United States and the remainder in Mexico (Hunt 1974). The river flows south from Colorado through the length of New Mexico and then forms the international boundary between Texas and Mexico along its 3,220-km route to the Gulf of Mexico.

The MRG study area (Fig. 2) consists of about 410 km of the Rio Grande from the outlet of Elephant Butte Reservoir, at river kilometer 2,224 (mile 1,382), north of El Paso, Texas, to about 16 km upstream from the confluence of the Rio Chama at Velarde, New Mexico, at river kilo-

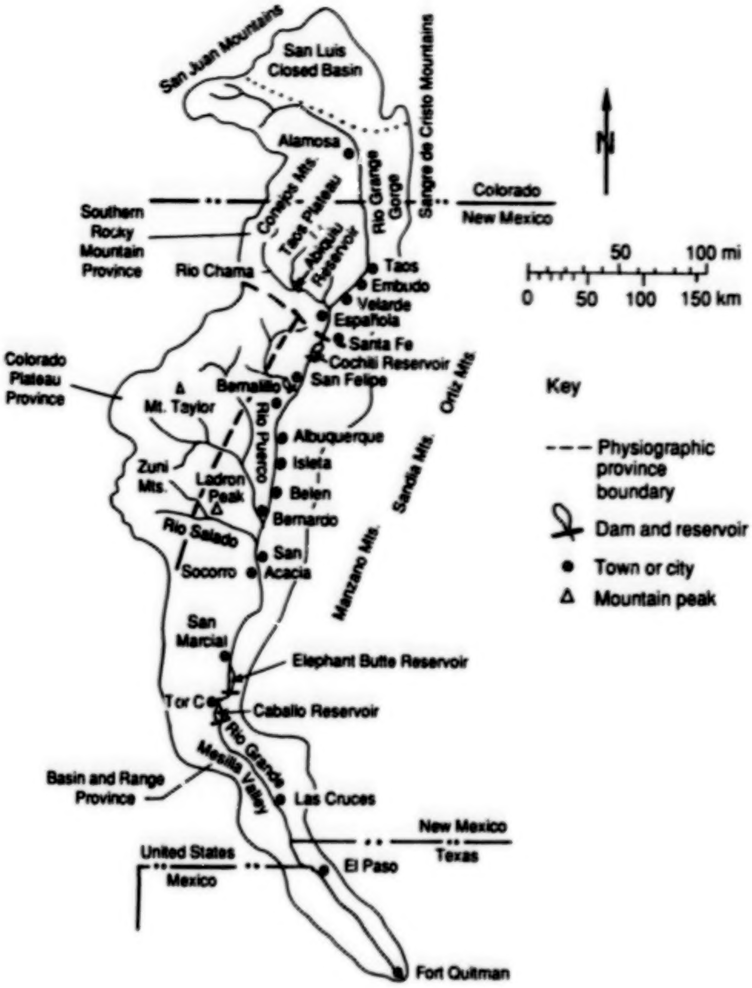


Fig. 1. Map of the Rio Grande drainage basin.

meter 2,639 (mile 1,640; U.S. Geological Survey 1987). The drainage basin area above Elephant Butte is about 76,275 km^2, including 7,615 km^2 in the Closed Basin of the San Luis Valley in Colorado. Above Velarde the drainage basin area is about 27,325 km^2, including the Closed Basin. The Rio Chama, one of the most important tributaries in the study area, has its headwaters in the Jemez, Conejos, and San Juan Mountains of New Mexico and Colorado. The Rio Chama drainage basin area is about 8,160 km^2.

Physiography and Geology

Location of the Rio Grande, physiography of the region, and patterns of cultural development in the area are intimately related to the regional geologic setting. Hydrologic characteristics of the Rio Grande basin, such as infiltration, runoff, and sediment discharge, are also dependent on the geology, geomorphic evolution of tributary basins, and late Tertiary and Quaternary geologic and climatic history. Structural geology (such as faults and folds) of a region governs spatial and geometric relations of rock units in that region. Geologic structures and lithology influence the development of topographic features, river and tributary position, and landscape evolution. Tectonic activity can produce measurable effects on channel and sediment transport characteristics (Ouchi 1983, 1985; Schumm 1986).

The location of the Rio Grande is controlled by the dominant geologic structure of the region, the Rio Grande Rift. The Rio Grande Rift is a linear topographic feature that separates the Great Plains from the Colorado Plateau (Hawley 1978).

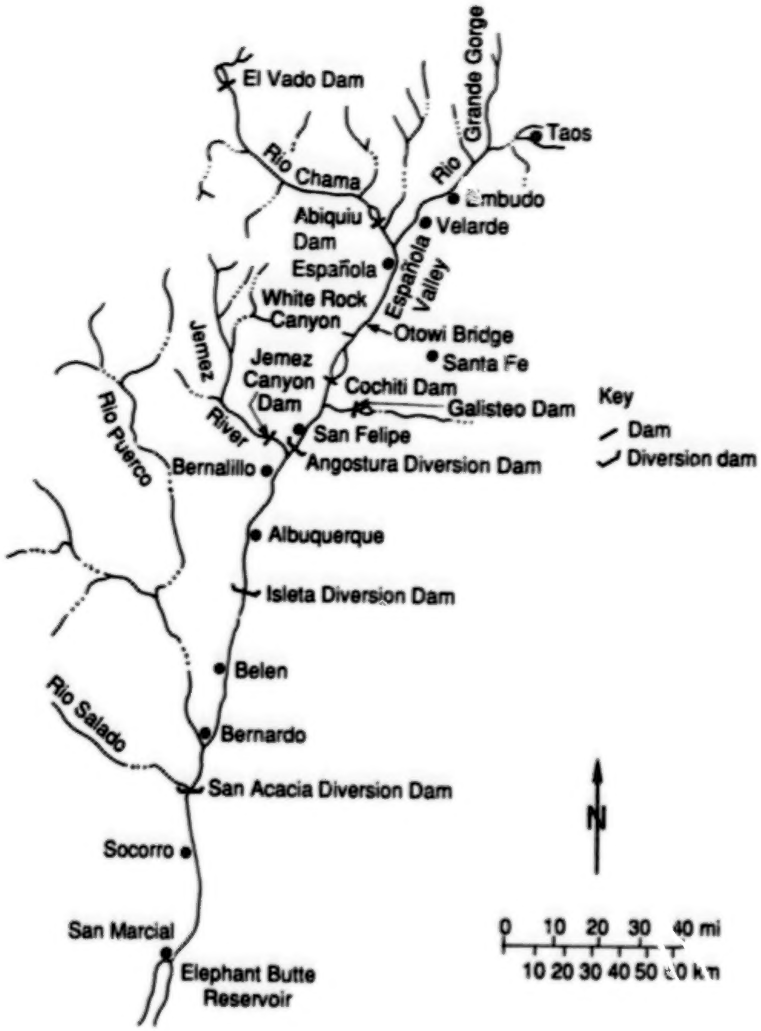


Fig. 2. Map of the Middle Rio Grande.

Mountain ranges, which can influence weather patterns, are a direct result of geologic processes. The location of early trade routes was influenced by the spatial arrangement of mountain ranges that were natural barriers to travellers. Indigenous populations and early settlers in the region sought areas of suitable climate, access, and availability of water. Thus, the presence of the Rio Grande Rift has influenced human settlement patterns in the region.

The extent and type of bedrock can influence infiltration and runoff characteristics. These factors can dramatically influence tributary basin evolution, discharge characteristics, main stem flow, and main stem evolution and integration (Leopold et al. 1964; Schumm 1977; Richards 1982; Kelson 1986; Wells et al. 1987). Bedrock type influences vegetation types and densities, which in turn influence infiltration and runoff, landscape stability, soil development, and sediment supply. Soil development is important because natural, progressive changes in physical properties of soils occurring through time alter the nature of the land surface, including vegetation communities, infiltration (decreases with increasing age), erosion, and runoff and discharge.

Physiographic Provinces and Geology of the Rio Grande Drainage Basin

The Rio Grande basin lies in five physiographic provinces: the Coastal Plain, the Great Plains, the Basin and Range, the Colorado Plateau, and the Southern Rocky Mountains (Hunt 1974). The MRG and its tributaries are located within the latter three provinces (Fig. 1). That part of the Rio Grande below El Paso lies within the Great Plains and Coastal Plain and is not included in this report.

Southern Rocky Mountains province. The Rio Grande originates in the high mountain peaks of southern Colorado. From its origin in Colorado to north of Santa Fe, New Mexico, the drainage basin is located within the Southern Rocky Mountains physiographic province (Fig. 1). The Southern Rocky Mountains province containing the Rio Grande Basin consists of relatively continuous high mountain ranges (2,440–4,270 m) and intervening high plains, or parklands (1,830–2,440 m). The geology of this region is characterized by Precambrian metamorphic complexes and plutonic igneous bodies, Paleozoic sedimentary sequences, and Cenozoic volcanic rocks.

The higher elevations of mountain ranges in Colorado and New Mexico experienced Pleistocene glaciation and also display evidence of Holocene neoglacial activity (Richmond 1965, 1986; Wesling 1988). The high plains area is found between the Sangre de Cristo and San Juan Mountains and is known as the San Luis Valley in southern Colorado and the Taos Plateau in northern New Mexico. The northern half of the San Luis Valley lies within a closed basin, from which there is no natural outlet for surface flow, and is separated from the southern half of the valley by a low topographic divide.

The Continental Divide forms much of the western boundary of the Rio Grande basin in the Southern Rocky Mountains and the Colorado Plateau provinces. Here the boundary is defined by the Rocky Mountains and San Juan Mountains in southern Colorado and the Jemez Mountains in New Mexico. The Jemez Mountains are the remnants of a major late Tertiary and Quaternary volcanic center. The eastern boundary of the watershed within the Southern Rocky Mountains province is formed by the Sangre de Cristo Range, a southern extension of the Rocky Mountains.

From its headwaters the Rio Grande flows mostly east and southeast to near Alamosa, Colorado, and then turns south. The river is entrenched across the Taos Plateau about 40 km north of the New Mexico state line and remains entrenched for about 110 km in a narrow, deep canyon known as the Rio Grande Gorge of New Mexico. The gorge is cut into the Taos Plateau, which is capped by Plio-Pleistocene Servilleta basalt and volcanic rocks associated with volcanism in the region 2 million to 4.5 million years ago (Lipman and Mehnert 1979). The canyon terminates abruptly near Velarde at the head of the Española Valley. For the purposes of this report, this is the upstream limit of the MRG, although various federal, state, and local agencies have their own terminology and designations for subbasin areas.

Colorado Plateau province. The west-central portion of the basin is situated within the Colorado Plateau province (Fig. 1). This province is a broad, generally low-relief plateau region characterized by horizontal or gently deformed Paleozoic, Mesozoic, and Cenozoic rock strata. Numerous deep and broad canyons, mesas, and buttes are eroded into the colorful rock units. The plateau lies at elevations ranging from 1,830 to 2,440 m; isolated mountain masses within the province rise to more than 3,050 m.

The Rio Puerco and Rio Salado are two major tributaries to the Rio Grande that have the majority of their drainage basin area situated within this region. The Rio Puerco, the northern tributary, is bounded on the northeast by the Nacimiento Range (adjacent to the western margin of the Jemez Mountains) and on the west by the Zuni Mountains along the Continental Divide. Near the center of the Rio Puerco basin, Mount Taylor, the remnant of a late Cenozoic and Quaternary stratovolcano, rises to more than 3,050 m in contrast to the plateau lands. The Rio Salado drainage basin has similar topography to the Rio Puerco; however, with the exception of Ladron Peak on the northern boundary, the Rio Salado basin is not bounded by high mountain masses.

Basin and range province. The remaining Rio Grande drainage basin area lies within the Basin and Range, Great Plains, and Coastal Plains provinces (Fig. 1); the latter two are not discussed in this report. In New Mexico the Basin and Range province is characterized by distinct, isolated, high, subparallel, north–south oriented, linear mountain ranges paralleling the axis of the major geologic structural element, the Rio Grande Rift. The geometry of the Basin and Range province here is a result of a predominantly extensional tectonic environment. Most mountain ranges do not exceed 2,440 m, although the Sandia Mountains rise to more than 3,050 m. Valleys and plains situated between the mountain ranges have elevations from 1,220 to 1,830 m. The geology of this part of the Basin and Range consists of thick Miocene- to Quaternary-age sediments that filled the structural depression (Rio Grande Rift) beneath the course of the Rio Grande.

The eastern boundary of the basin in this region is formed (from north to south) by the Ortiz, Sandia, Manzano, Oscura, San Andres, Organ, and Franklin Mountains. The western boundary is formed by the edge of the Colorado Plateau and the Black Range. Contained within the basin along the east side of the Rio Grande are the Fra Cristobal Range and the Caballo Mountains. The Magdalena and San Mateo Mountains lie between the Rio Grande and the Black Range in the western part of the watershed.

Physiography and Geology of the Middle Rio Grande

The MRG lies within the Basin and Range and Southern Rocky Mountain physiographic provinces, although some western tributaries head in parts of the Colorado Plateau province (Figs. 1 and 2). The MRG valley is generally narrow, ranging from less than a kilometer in narrow or incised canyons, to about 10 km in other parts. The Rio Grande is situated in an alluvial valley developed in the rift-fill sediments of the Santa Fe Group. Eastern tributaries from Española to Elephant Butte are developed on thick Tertiary rift-fill sediments and uplifted Precambrian, Mesozoic, and Paleozoic rock units on the flanking mountains. Western tributaries originate on Paleozoic and Mesozoic sedimentary rocks of the Colorado Plateau, and on volcanic rocks from the Jemez volcanic field and Albuquerque Volcanoes south to the Socorro region.

The MRG begins north of Española along the rugged southern edge of the eroded Taos Plateau, the southern extension of the San Luis Valley, where the Rio Grande exits the Rio Grande Gorge and enters the Española Valley (Kelley 1979a, 1979b). The Española Valley is about 50 km long and has an average elevation of about 1,675 m. The valley is flanked by mesas that may be 100–300 m high and are, in many places, capped by basalts. The Española Valley area is characterized by pediment surfaces (or erosional surfaces capped by thin veneers of alluvial sediments), which were first recognized by Johnson (1903) and later studied in more detail by Bryan (1938) and Stearns (1953). The Rio Grande exits the Española Valley through another gorge, White Rock Canyon, located about 30 km west of Santa Fe at Cochiti Reservoir. White Rock Canyon is a narrow gorge about 40 km long cut into the southern extension of the high plain. The Rio Grande leaves the Southern Rocky Mountain province upon exiting White Rock Canyon.

From near Cochiti to Elephant Butte the eastern boundary of the drainage basin is relatively close to the river, and the high mountain ranges connect with the river by a gently sloping piedmont consisting of coalescing alluvial fans and pediment surfaces. Flights of fluvial terraces that parallel the existing river record former base levels of the ancient Rio Grande. Areas characterized by high tributary sediment input, such as near the confluence of the Rio Salado with the Rio Grande, may have localized sand dunes and dune fields. Subbasins of the MRG are related to the rift structures and are identified by constrictions of the valley, such as those at San Felipe (Santo Domingo subbasin), Isleta (Albuquerque subbasin), San Acacia (Belen subbasin), and San Marcial (Socorro subbasin).

The Quaternary geologic history of the MRG is important in understanding the evolution and hydrologic behavior of the MRG and tributary basins. The geomorphology of the region is characterized by numerous well-preserved erosional surfaces extending toward the axis of the basin from the piedmont-mountain front junction. These surfaces consist of veneers of pediment gravels overlying bevelled bedrock surfaces. Near the axis of the basin the pediment surfaces merge with terraces representing former base levels of the ancestral Rio Grande.

The oldest pediment surfaces and terraces are characterized by the presence of very well-developed soils that typically possess strongly indurated, thick calcium carbonate horizons below (and engulfing) the clay-rich B horizon. In some places the land surface may be deeply eroded such that the indurated, impermeable calcium carbonate horizon is at or very near the surface. This condition can have dramatic, and at times catastrophic, effects on surface runoff during intense rainstorms. Younger pediment surfaces and terraces have progressively less well-developed clay-rich B horizons and calcic horizons and progressively more permeability. The youngest land surfaces (e.g., floodplains) have little or no soil developed on them and are typically most permeable.

Structural Geology of the Middle Rio Grande Region

Research over the past 15 years has provided a better understanding of the geologic and geomorphic history of the Rio Grande and its integration into a through-flowing system (Bachman and Mehnert 1978). At present the Rio Grande flows along the axis of the Rio Grande Rift. The rift consists of a series of well-defined, asymmetrical, north-northwest-trending grabens (or structural basins) extending from central Colorado to northern Mexico for a distance of more than 950 km (Baldridge et al. 1984). These grabens evolved during late Cenozoic extension in the Basin and Range province (Woodward and Ingersoll 1979). The grabens are filled with Miocene- to Quaternary-age sedimentary and volcanic rocks that, in places, exceed 7,000 m in thickness and may have total stratigraphic displacements of greater than 10,000 m (Black 1982). The rift is characterized by active extension, high heat flow, high seismicity, local tectonic uplift, and recent volcanism (Jurdy and Brocher 1980).

The grabens have formed a series of northerly trending, linked depositional basins flanked by uplifts of various types (Kelley 1952, 1977, 1979a, 1982; Lagasse 1980). Each depositional basin contained its own ephemeral lake before complete integration of the Rio Grande fluvial system. Through time each depositional basin filled and was integrated with adjacent basins as canyons were cut across the intervening bedrock sills that separate the structural basins. At present the river flows through narrow canyons (e.g., White Rock Canyon) as it crosses from one structural basin to another.

Seismic activity in the region is restricted primarily to the Rio Grande Rift zone. Measurements over the past 100 years indicate that the Socorro–Albuquerque part of the rift has experienced considerable but localized earthquake activity (Sanford 1963; Sanford et al. 1972, 1979; Lagasse 1980; Northrop 1982; Olsen et al. 1982). Studies in the Socorro region of the rift indicate active crustal deformation thought to be related to the Socorro magma body at shallow depth in the region (Sanford et al. 1973). Measurements from 1934 to 1978 show uplift of about 10 cm (Reilinger et al. 1980), and studies by Larsen and Reilinger (1983) show uplift of about 13.7 cm from 1912 to 1951 and subsidence of 6–10 cm over the same period. Tectonic activity is not unique to the Socorro region. Work by Machette (1978, 1982), Machette and McGimsey (1983), McCalpin (1983), Personius and Machette (1984), and Menges (1987) indicates a substantial amount of neotectonic activity from south of Socorro to the western flank of the Sangre de Cristo Range in southern Colorado. This deformation in the rift is important in terms of fluvial behavior of the Rio Grande in this region. Changes in channel gradient, channel pattern, and sediment transport characteristics can be expected both upstream and downstream of a tectonic disturbance (Schumm 1977, 1986).

Climate of the Middle Rio Grande and Rio Grande Basin

The Rio Grande drainage basin is located in a transitional climatic zone between the Gulf of Mexico and the Pacific rainfall provinces. Complex meteorological conditions exist in this region, and these conditions are further complicated by the orographic influence of surrounding mountain ranges and global circulation patterns.

The Rio Grande basin has an arid to semiarid climate typical of the southwestern United States. The climate is characterized by abundant sunshine, low relative humidity, light precipitation, and wide diurnal temperature fluctuation. The climate of the drainage basin upstream from Bernalillo is semiarid; the region downstream from Belen has an arid climate (Tuan et al. 1973; Fig. 3). Higher mountain regions have temperate climates. Average annual precipitation varies from 178 to 380 mm over two-thirds of the basin and may exceed 635 mm only in the high mountain areas. Winters are generally dry, and snow rarely remains on the ground at low elevations for more than 24 h. Snowfall in the high mountains composes 30–75% of the total annual precipitation; in the remainder of the basin snowfall composes less than 25% of the annual precipitation. Summer precipitation supplies almost half of the annual moisture. Most of the rain falls in brief, though sometimes intense, convective thunderstorms.

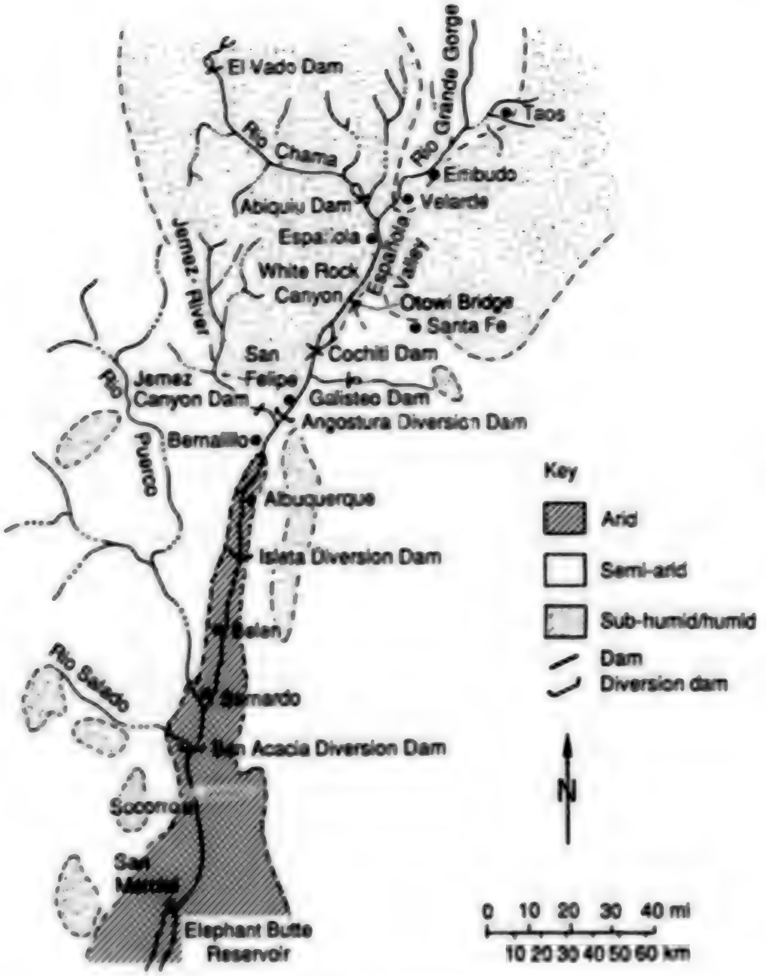


Fig. 2. Map of climatic zones of the Middle Rio Grande (U.S. Bureau of Reclamation 1977).

These summer thunderstorms have a considerable moderating effect on daytime temperatures. Prevailing winds are from the southwest and typically are continuous during the spring months. Evaporation rate is high throughout the lower elevations of the basin and is highest in the southern part of the basin, where arid conditions exist.

Temperatures are characteristic of high-altitude, dry continental climates. Average temperature ranges are from minimums of 2.9° to 8.3° C to maximums of 23° to 24° C along the river valley. Mean annual temperature range is about 12.2° to 16.1° C. Freezing temperatures can occur at any time in the high mountain elevations. Average summer temperatures in the upper basin regions and along the drainage divides may average >5° C lower than in the valley regions. The average frost-free period in the valley region extends from May to October. The highest temperatures in the valley region occur in July and the lowest in January.

The major part of precipitation in the basin is derived from the tropical region of the Gulf of Mexico (Jetton and Kirby 1970; Tuan et al. 1973). Hurricane activity off the west coast of Mexico may at times import significant amounts of moist unstable air, which can result in major storms. The influence of polar Pacific and polar continental air masses on the position of the jet stream is important in how they affect the magnitude and location of precipitation within the drainage basin.

Storms in the region are of two types: local thunderstorms that result from orographic or convective lifting, and frontal storms resulting from the interaction of two or more air masses. Generally, precipitation during storm periods lasts less than 24 h, although precipitation intensity may be extremely high at some locations within the general storm area. Precipitation periods lasting more than 24 h are generally associated with tropical disturbances related to hurricane activity in the

Gulf of Mexico or in the Pacific Ocean off the west coast of Mexico.

Storms are seasonal with respect to type and magnitude. Summer months, June through August, are normally characterized by intermittent importations of tropical maritime air masses. Orographic lifting or convective action results in isolated shower activity, which is often intense but generally localized. General activity of this type may occur at many points simultaneously and may infrequently result in a general major storm.

Vigorous air-mass activity occurs during winter months, November through February, and is characterized by a series of cold fronts of polar Pacific air moving eastward or northeastward (Maker et al. 1972). Precipitation in the mountain regions occurs as snow, while lower elevations of the central basin may receive snow or moderate rains. Due to the northerly path of storms, precipitation in the southern part of the basin is generally low.

The periods transitional to summer and winter (March through May and September through October) are associated with some of the largest flood-generating storms. Greater temperature differences between air masses are reflected in increased air-mass instability. The simultaneous movements of various types of air masses into the region are more pronounced than during other periods. During spring, heavy snowfall may occur in the mountains in conjunction with general rains elsewhere in the basin. During the later spring months and fall, storm activity may be characterized by high-intensity rains over large portions of the basin.

Runoff in the basin comes largely from spring snowmelt and spring and summer convective thunderstorms; it ranges from <25 mm to >255 mm in the mountains. About 70% of the runoff occurs from May to August during snowmelt and thunderstorm activity.

Climatic Records

Climatic data-gathering stations in the basin are neither abundant nor systematic in their collection of data, which is due in part to problems associated with mechanical reliability of data collection devices, length of record, vandalism, and maintenance. For example, during a recent study by the U.S. Army Corps of Engineers (COE) on flood protection in the Albuquerque region, hydrologic models were based on three rainfall-runoff data collection stations for the area of about 2,590 km^2. The gages, which had functioned for less than 9 years, were 3 of 13 stations installed by the U.S. Geological Survey (USGS). Several of the stations had been vandalized, making their records unreliable and noncontinuous. These types of problems reduce the usefulness and reliability of climatic data in long-term climatic and hydrologic models.

Weather records have been kept since 1941 at the Albuquerque International Airport by the National Weather Service and the National Oceanic and Atmospheric Administration (NOAA). Similarly, records have been kept for several decades at metropolitan areas such as Santa Fe, Taos, Española, Socorro, and Truth or Consequences.

Weather and rainfall-runoff stations are also installed periodically in relation to short-term studies or projects that may require climatic data (e.g., environmental impact studies). Recording stations may also be installed in response to unusual climatic events that result in damage to the environment or urban areas. For example, high-intensity rainfall events during July 1988 caused considerable flood damage on the piedmont slope in and around Albuquerque. A number of new recording stations were subsequently installed in tributary basins responsible for the floods and in others that pose potential threats to current or future urban areas.

For New Mexico, 44 long-term temperature and 32 precipitation data collection stations have been operated since 1893 (Bradley et al. 1982). Stations located within the Rio Grande basin of New Mexico are listed in Table 1 and shown on Fig. 4. Additional sources of long-term climate data include the following:

- *Bulletin W*, published by the U.S. Weather Bureau for data before 1930.
- Digitized data from the National Climatic Center, generally only available for the period after 1930 or after 1948.
- *Climatological Data*, published monthly by NOAA for recent data and data not available on magnetic tape.
- *Local Climatological Data*, published by NOAA for selected stations, containing data for 1931–60 or for 30 years before publication date.

Table 1. *Long-term temperature and precipitation stations in the Rio Grande drainage basin of New Mexico (Bradley et al. 1982).*

I.D. number	Station name	Latitude[a]	Longitude[b]	Elevation (m)	Record length
		Precipitation stations			
0796NME	Bateman	3631	10619	2,713	1909–1970
1664NME	Chama	3655	10635	2,393	1905–1970
2848NME	Elephant Butte	3309	10711	1,396	1907–1970
4369NME	Jemez Springs	3547	10641	1,906	1910–1970
5147NME	Los Lunas	3448	10644	1,489	1889–1970
5363NME	Magdalena	3407	10714	1,993	1905–1970
7323NME	Red River	3642	10524	2,644	1906–1970
8072NME	Santa Fe	3541	10554	2,196	1850–1970
8387NME	Socorro	3405	10653	1,398	1891–1970
8668NME	Taos	3622	10537	2,117	1901–1970
8873NME	Tijeras R S	3504	10623	1,920	1910–1962
9085NME	Tres Piedras	3640	10559	2,475	1905–1970
9820NME	Wolf Canyon	3558	10646	2,484	1912–1970
		Temperature stations			
1664NME	Chama	3655	10635	2,393	1905–1970
2848NME	Elephant Butte	3309	10711	1,396	1908–1970
4369NME	Jemez Springs	3547	10641	1,906	1910–1970
5084NME	Los Alamos	3552	10618	2,259	1919–1970
5147NME	Los Lunas	3448	10644	1,489	1889–1970
5363NME	Magdalena	3407	10714	1,993	1908–1970
7323NME	Red River	3642	10524	2,644	1909–1970
8072NME	Santa Fe	3541	10554	2,196	1908–1970
8668NME	Taos	3622	10537	2,117	1901–1970
9085NME	Tres Piedras	3640	10559	2,475	1905–1970
9820NME	Wolf Canyon	3558	10646	2,484	1912–1970

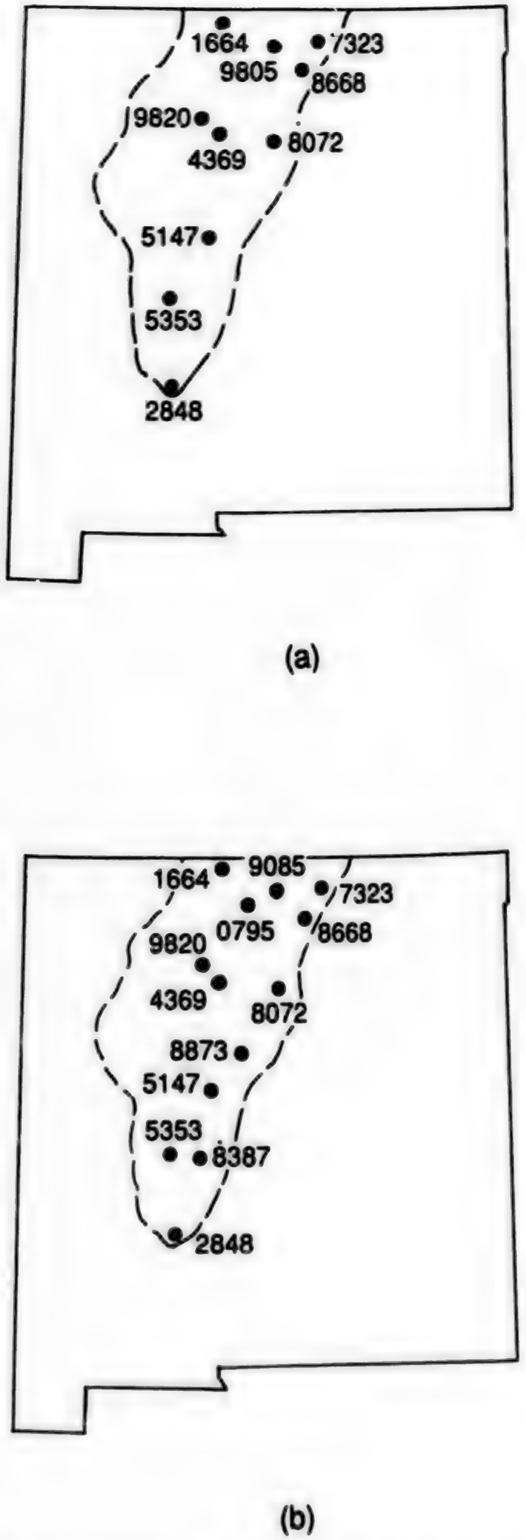
[a] Latitude is given in degrees (first two digits) and minutes (last two digits).

[b] Longitude is given in degrees (first three digits) and minutes (last two digits).

Climatography of the United States, 60, "Climates of the States," first issued by NOAA and now one of several in the series "Periodic Summarization of Climate" prepared by the National Climatic Center in Asheville, North Carolina.

K. Kunkle, the state climatologist at New Mexico State University, currently has on record all climatic data available for the state of New Mexico. An additional source for climatic data is U.S. West Optical Publishing in Denver, Colorado. U.S. West Optical has climatic records from more than 25,000 cooperating stations across the United States. Data are contained on 5-inch compact discs that are capable of storing 630 megabytes. U.S. West Optical also provides software to perform a variety of statistical and graphical analyses.

Additional treatments of climatic data are available. Balling (1986) investigated long-term temporal and spatial patterns of warm-season precipitation events in the central United States, including New Mexico. These studies may be useful for evaluating diurnal variations in rainfall, analyzing individual events, forecasting weather, and verifying hydrologic models. Hesemeier et al. (1977) presented a compilation of drought bibliographic information useful in understanding the problems that water users along the Rio Grande have faced in the past and the problems that will need to be addressed in the future. Additional information concerning climate, physiography, geology, and resources of the Rio Grande is provided by the U.S. Department of Agriculture (1968, 1969a, 1969b, 1970).



(a)

(b)

Fig. 4. Location of (a) long-term temperature and (b) long-term precipitation stations in the Rio Grande drainage basin (Bradley et al. 1962).

Fluvial Characteristics of the Rio Grande

The physical nature of the Rio Grande, and its tributaries, varies with its position in the drainage basin. This is a direct reflection of the geology and topography of the physiographic regions traversed by the river. Gradient, channel pattern and width, discharge, and sediment load are variable throughout the length of the river. Discharge and sediment load characteristics will be discussed in more detail in separate sections.

Gradient of the Rio Grande

Relief is high in headwater regions, and tributary streams characteristically flow through steep canyons on their way to the San Luis Valley; gradients locally may be tens of meters per kilometer. The river has a gradient of about 0.56 m/km through the San Luis Valley. Through the Rio Grande Gorge, river slope ranges from 2.25 to >28.4 m/km. From Velarde to Cochiti Reservoir (the downstream end of White Rock Canyon) river gradient is about 1.9 m/km. From below Cochiti Dam to Elephant Butte the gradient is about 0.76 m/km.

Channel of the Rio Grande

The channel of the Rio Grande varies dramatically with geographic location within the river basin. Channel characteristics such as width and sinuosity are strongly influenced by position within the drainage basin and proximity to tributaries that discharge large volumes of sediment into the main stem.

The width of the Rio Grande Valley ranges from <200 m in the Rio Grande Gorge to 1.5–10 km from Velarde to Elephant Butte, with the exception of White Rock Canyon and the San Marcial Constriction. Short canyons or narrows also exist at San Felipe, Isleta, and San Acacia at the boundaries of subbasins within the Rio Grande Rift. The floodplain of the Rio Grande ranges from 150 m or less in the Rio Grande Gorge to greater than 1 km in the reaches from Velarde to White Rock Canyon and from Cochiti Dam to San Acacia.

The channel of the Rio Grande varies in width depending on location in the drainage basin. The channel is narrowest in the bedrock canyons and widest in the broad alluvial valleys downstream from Bernalillo. Generally, the channel is 60–90 m

Table 2. *Width of the cleared floodway of the Rio Grande (U.S. Bureau of Reclamation 1977).*

Reach	Period of clearing	Range in width of cleared floodway for each reach (m)	Estimated range in width of the whole floodway (m)
Española reach	1956–1958	105–140	500–800
Cochiti reach	1953–1974	50–450	70–1440
Albuquerque reach	1953–1974	110–450	75–920
Belen reach	1953–1974	105–720	150–930
Socorro reach	1951–1974	90–520	240–1500
San Marcial reach	1951–1974	130–470	210–675

wide, flows on a shifting sand and gravel substratum, and has low, poorly defined banks (Lagasse 1980). Floodway widths in the study area are variable (Table 2). The floodway is largely confined between earthen levees and is cleared for much of the length of the MRG, especially in urban areas and areas prone to highest aggradation. The floodplain contains a mixture of cottonwood (*Populus fremontii*), willow (*Salix* spp.), Russian-olive (*Elaeagnus angustifolia*), and salt cedar (*Tamarix chinensis*), which together form a dense growth of riparian woodland (known as bosque), interspersed with pasture and cultivated land (Lagasse 1981).

The Middle Rio Grande has a shifting alluvial channel that is characterized by bedload transport of medium-grained sand, except in narrow canyons, which typically have bedrock channels. Characteristic channel patterns displayed by the Rio Grande are low sinuosity meandering, straight, and braided meandering. Formation of sediment bars in the channel during low-flow periods and, in particular, during the recession of flood flows, together with rapid growth of vegetation, generally determine the channel configuration within the levees. In some places the floodway is unstable (i.e., the channel is not confined to a fixed position). In these areas, the channel has virtually no banks, and the bed of the river is at or above the land surface outside the levees due to sediment deposition between the levees. Braided meandering patterns are especially common downstream from major sediment- supplying tributaries such as the Rio Puerco and the Rio Salado and other small, unregulated, high-sediment-discharge tributaries in the reach below Cochiti Dam. The Rio Grande characteristically is meandering in the San Luis Valley region, straight to meandering through the gorge, and meandering and braided with some straight portions throughout the lower reaches. The channel is typically straight to meandering through the bedrock canyons of the constrictions.

Channel pattern can also change on a seasonal basis due to lower flow conditions and the inability of the river to effectively transport sediment delivered by tributaries. Channel pattern also may change during receding flood flows. The addition of numerous flood control and sediment control structures on the Rio Grande and tributaries has eliminated some of the problems formerly associated with flood-transported sediment discharged into the main stem. On the other hand, flood control structures have added to the problem of channel migration in some reaches of the river downstream of dams (Lagasse 1980, 1981).

Discharge of the Rio Grande

The Rio Grande is a perennial river that receives the majority of its discharge from late spring snowmelt and rain storms. Summer convective storms produce runoff in isolated parts of the basin, which may alter the hydrology for brief periods. The majority of the discharge for the MRG comes from the headwaters of the Rio Grande in Colorado and from the Rio Chama. The Rio Chama is assured of perennial discharge because of the San Juan-Chama Transmountain Diversion (SJC) Project and dams along the Rio Chama and its tributaries (U.S. Bureau of Reclamation 1981). Average annual discharge for the Rio Grande into the Gulf of Mexico is about 9,000,000 acre-feet (Hunt 1974). The annual runoff in headwater regions ranges from 215,000 to 1,100,000 acre-feet,

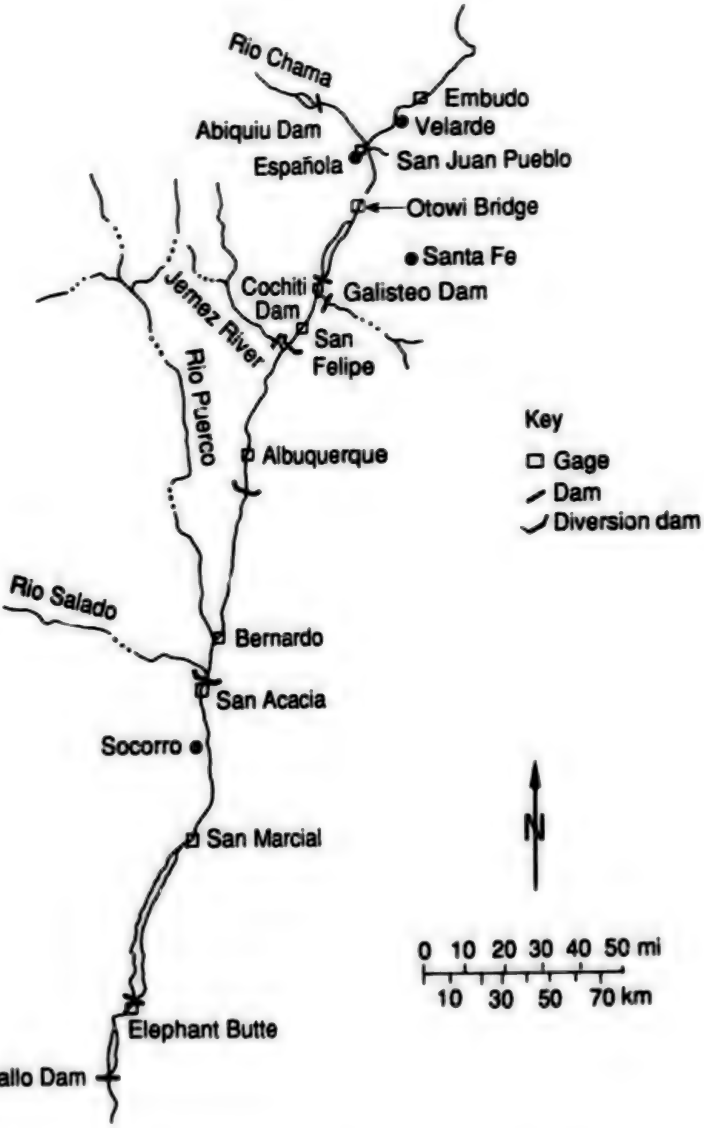


Fig. 5. Location of gaging stations on the main stem Middle Rio Grande.

with an average of 660,000 acre-feet (U.S. Army Corps of Engineers 1989).

The Rio Grande has some of the longest streamgaging records in the United States; however, these records are not necessarily the most reliable. The Embudo gage near the southern end of the Rio Grande Gorge (Fig. 5) was installed in 1889 and has nearly 100 years of record, although not continuous. Reliability and continuity of stream gaging station data are problems throughout the United States, and the Rio Grande is no exception. Within the Rio Grande drainage basin above Elephant Butte Dam there have been more than 100 stream gaging stations since record keeping began.

The main stem discharge of the MRG can be characterized by 10 gaging stations: Embudo upstream from Velarde, San Juan Pueblo (discontinued in 1987), Otowi Bridge near San Ildefonso, below Cochiti Dam, San Felipe, Albuquerque, Rio Grande Floodway near Bernardo, Rio Grande Floodway at San Acacia, Rio Grande Floodway at San Marcial, and below Elephant Butte Reservoir (Fig. 5). Annual average flow at Otowi Bridge is about 1,100,000 acre-feet; downstream at San Marcial above Elephant Butte Reservoir, the annual average flow is 745,000 acre-feet (U.S. Army Corps of Engineers 1989). Table 3 summarizes the average annual and maximum and minimum daily discharges for the 10 gaging stations.

Table 3. *Discharge data for main stem gaging stations on the Middle Rio Grande (compiled from U.S. Geological Survey 1987).*

Station I.D. number	Name	Latitude (_°_'_")	Longitude (_°_'_")	Period of record	Average discharge (cfs)[a]	Extreme discharges[b]	
						Maximum (cfs)	Minimum (cfs)
08279500	Embudo	36-12-20	105-57-49	1889 to present	1,236	16,209	141
08281100	San Juan Pueblo[c]	36-03-58	106-04-34	1963–87	812	8,228	71
08313000	Otowi Bridge	35-52-29	106-08-30	1895–05 1909 to present	1,519	24,367	71
08317400	Cochiti Dam	35-37-05	106-19-24	1970 to present	Not available	10,312	0.35
08319000	San Felipe	35-26-39	106-26-23	1925 to present	1,377 (1926–1973)[d] 1,624 (1973–1987)[e]	27,298	32
08330000	Albuquerque	35-05-21	106-40-48	1941 to present	1,059 (1942–1973)[d] 1,483 (1973–1987)[e]	25,003	0
08332010	Bernardo	34-25-01	106-48-00	1936 to present	1,130 (1937–1958)[d] 883 (1959–1973)[d,h] 1,483 (1973–1987)[e,h]	21,012	0
08354900	San Acacia	34-15-23	106-53-18	1937 to present	1,201 (1937–1958)[f] 918 (1959–1973)[d,g] 1,519 (1974–1987)[e,g]	27,369	0
08358400	San Marcial	33-40-50	106-59-30	1964 to present	1,271 (1895–1987) 742 (1965–1987)	49,970	0
08361000	Elephant Butte	33-08-54	107-12-22	1915 to present	989	8,193	0

[a] cfs = cubic feet per second.
[b] Extremes are for period of record.
[c] Gage discontinued in 1987.
[d] Pre-Cochiti Dam closure.
[e] Post-Cochiti Dam closure.
[f] Pre-conveyance channel; does not include Socorro Main Canal.
[g] Includes floodway, conveyance channel, Socorro Main Canal.
[h] Includes floodway, conveyance channel, Bernardo Interior Drain, lower San Juan Riverside Drain.

Due to the extensive agricultural activity in the MRG nearly all Rio Grande water is appropriated. Releases from upstream reservoirs, under nonflood conditions, are regulated to make reservoir outflows equal to inflows in order to meet water demands. Irrigation accounts for about 90% of all Rio Grande water used in the region; however, water diverted for agricultural purposes is not fully utilized. About 67% of all diverted water does not reach farmlands. This water consists of transportation losses (spills, seepage losses to unlined canals), evapotranspiration, and groundwater recharge. About 45% of all water diverted eventually returns to the river. About 33% of water diverted reaches the farms; crops use about 55% of this amount (or about 20% of the total diverted from the river). About 35% of all diverted water is lost to evapotranspiration or groundwater recharge (U.S. Army Corps of Engineers 1979).

Another source of discharge that will not be discussed is sewage treatment plants. Water from these plants is discharged year-round in the large metropolitan areas and probably has a smoothing effect on the annual discharge hydrograph of the Rio Grande (Lagasse 1980).

Detailed information concerning gage location, period of record, and maximum and minimum stage and discharge for the period of record for the Rio Grande main stem and tributaries can be obtained through the USGS Water-Data Reports for New Mexico and older USGS Water Supply Papers. Complete discharge data for the period of record for all gages can be obtained through the USGS Water Resources Division and the USGS WATSTORE data base. The USGS is evaluating the possibility of downloading data from magnetic tape to 5.25-inch floppy diskettes.

An additional source of discharge data is U.S. West Optical Publishing in Denver, Colorado. Their "Hydrodata System," available for sale, includes discharge data for the period of record for most of the United States (1.2 gigabytes representing more than 600,000 station-years of data). Data for the western United States are stored on one 5-inch compact disc and can be accessed with a personal computer. Data for the current year, however, may not be an official USGS updated version and may not be correct (L. Beal, USGS, Albuquerque, New Mexico, personal communication). U.S. West Optical Publishing also has software to perform statistical and graphical analyses of stream discharge data.

The USGS also maintains rating curves for all gages and provides necessary updates on stage-discharge relations at measured cross sections. Rating curves for many gages must be revised frequently because of shifting alluvial channels, floodway maintenance, and construction of conveyance channels.

Sediment Load of the Rio Grande and Tributaries

Suspended sediment loads for the Rio Grande and tributaries are variable. These are regulated to a certain degree by flood and sediment control structures, especially in the regions above Albuquerque. Tributaries, however, can be major contributors of sediment to the Rio Grande. An increase in sediment supplied to the Rio Grande can have dramatic effects on river behavior and geomorphology both upstream and downstream (Schumm 1977; Lagasse 1980, 1981).

At Otowi Bridge the maximum daily suspended sediment load of 332,000 t was recorded in 1961 and the minimum of 2.7 t was recorded in 1963; in 1987 the maximum daily suspended sediment load was 23,000 t (U.S. Geological Survey 1987). The maximum recorded daily suspended sediment load 225 km downstream at San Acacia was 1,597,000 t; there is no discharge of water or sediment on many days of most years. The 1987 maximum and minimum daily suspended sediment loads were 180,000 t and 5.4 t, respectively.

Sediment data for the Rio Grande just below Cochiti Dam and for the Rio Puerco illustrate the influence of main stem impoundments and tributary contributions on sediment loads. Below Cochiti Dam the maximum daily recorded suspended sediment load was 4,580 t and the minimum was 0.02 t. The 1987 maximum and minimum suspended sediment loads were 442 t and 15 t. Thus, there is a deposition of thousands of tons of sediment daily in the 40-km reach between Otowi Bridge and Cochiti Dam, which indicates that sediment from the upper basin region of the Rio Grande is effectively trapped by Cochiti Reservoir. The same situation exists for sediment transported by tributaries of the Rio Chama and trapped in reservoirs on the Rio Chama.

In contrast, sediment contributions from nonregulated tributary basins can exceed depletions in sediment due to impoundment by main stem or tributary dams. The major tributaries of the Rio Grande are the Rio Chama, Jemez River, Rio Puerco, and Rio Salado (Fig. 2). The Rio Chama has an area of more than 8,000 km^2 and contributes more discharge (by one order of magnitude and a factor of two) than the Rio Puerco, which has an 18,900-km^2 drainage basin area. At present the Rio Puerco and Rio Salado deliver much more sediment to the Rio Grande than does the Rio Chama because there are dams on the Rio Chama. The Jemez River has a drainage area of 2,690 km^2 and a discharge about twice as large as the Rio Puerco, but it contributes little sediment to the Rio Grande because of Jemez Canyon Dam.

The ephemeral Rio Puerco is well known for its high sediment concentrations, which have exceeded 680,000 mg/L, 75% of which may be sand (Nordin 1963). This amount represents about 68% sediment by weight. In comparison, turbulent water floods are 1% to 40% sediment by weight, and debris flows are 70% to 90% sediment by weight (Costa 1984). The maximum daily suspended sediment load on record for the Rio Puerco is 2,032,000 t. The Rio Puerco lacks discharge of water or sediment for many days of the year (Heath 1983), and up to 82% of the sediment transported by this tributary occurs during events that recur about once per year (Leopold et al. 1964). The maximum daily suspended sediment load in 1987 was 212,000 t.

History of Water Development Along the Rio Grande

Water is a precious resource in semiarid and arid regions. Early settlers to the Rio Grande valley undoubtedly found the climate of the region to their liking, and water was accessible in the inner valley. Streamflows were probably similar to those today, highly dependent on sufficient winter snowpack, spring snowmelt and rains, and summer thunderstorms. An increasing population in the region made regulation of Rio Grande flows a necessity as demands were made for equal sharing of water for agricultural and domestic purposes in dry years as well as years of normal runoff. Increasing demand for water from both sides of the international border led to legal battles that attempted to provide an equitable solution to the problem. The Rio Grande now is regulated throughout its length and is able to supply water to users along the waterway. The following section presents a brief, chronological summary of water use and development along the Rio Grande.

Early Development of Water Resources

Irrigation diversions have been in operation in parts of New Mexico since the tenth, eleventh, and twelfth centuries (Christiansen 1973; Gillespie 1983; Wozniak 1987), well before the arrival of Spanish explorers. Many prehistorians presume that the irrigation systems in use by modern Pueblo Indians were inherited from late prehistoric peoples who used irrigation and floodwater farming in their agricultural practices along the Rio Grande valley. Cordell (1979, 1984a, 1984b) noted that the late prehistoric cultures were probably poorly equipped technologically to deal with the risks involved in floodwater farming on the floodplain. In fact, prehistoric cultures constructed extensive water- and sediment-control structures on uplands, away from the river, in order to engage in agricultural activities relying entirely on runoff from rainfall.

From the 1500's to 1800's Spanish colonization occurred, and development of acequias, or canals, for irrigation purposes began. The Spanish settlers in the Rio Grande valley supposedly patterned their community irrigation ditches after those of the Pueblo Indians (Wozniak 1987).

In the late 19th century, Spanish and European-American settlers in south-central Colorado built a series of community irrigation ditches in the San Luis Valley. By the late 1880's the MRG was filled with irrigation systems. As much as 50,600 ha of land may have been under irrigation between Cochiti and San Marcial, although this figure is not universally accepted. The area may have represented the total amount of land in cultivation or the total available land in the MRG (Wozniak 1987).

By the late 1890's the greatest practical amount of streamflow had been diverted for irrigation. Irrigation demands and drought years created irrigation shortages in the Mesilla Valley and in Mexico. The great demand for and use of irrigation water in Colorado and New Mexico caused reduced summer flows in the Rio Grande, and El Paso experienced dry river-bed conditions with increasing frequency and for greater lengths of time (U.S. Bureau of Reclamation 1981). Mexico, which depended on the Rio Grande for irrigation and domestic water, launched a protest over the dwindling supply. The International Boundary and Water Commission (IBWC) reviewed and investigated the complaint and put a moratorium on further water development along the Rio Grande in New Mexico and Colorado until the problem could be resolved. A storage facility was needed if the United States hoped to satisfy the claims made by Mexico.

Water Development in the Lower Middle Rio Grande

As early as 1888 a dam was proposed in the Mesilla Valley 5 km north of El Paso, Texas, to alleviate problems facing farmers in Texas and Mexico, such as flooding, natural droughts, and drought-like conditions brought about by extensive irrigation in northern New Mexico and Colorado (Mueller 1978). About the time that the dam was to be constructed in the mid 1890's the Rio Grande Dam and Irrigation Company obtained a charter from the Department of the Interior to build a private dam near Engle, New Mexico, at Elephant Butte, about 240 km upstream from El Paso; however, years of legal struggles and financial problems prevented the irrigation company from building the dam at Elephant Butte, and its charter expired in 1903 (Clark 1975). Severe drought conditions in 1902 and 1903 brought more complaints by Mexico, and the IBWC began to investigate the claims that Mexico was not receiving its fair share of water.

The Reclamation Act of 1902 and the Treaty of 1906 with Mexico

The Reclamation Act of 1902 provided for authorization and construction of federal reclamation (irrigation) projects and gave direction to previously unrestricted irrigation projects. The act and the drought conditions in 1902 and 1903 prompted the United States to evaluate water availability in the region. Surveys were begun in 1903, and a feasibility report was completed in 1904. The report concluded that a reservoir could be created by constructing a dam at Elephant Butte, New Mexico. This dam and reservoir could provide sufficient water to meet the requirements of all interests, and Congress authorized construction in 1905. The decision to build the dam was influenced by negotiations with Mexico over water rights. Soon after, in 1906, the treaty between Mexico and the United States was negotiated; it guaranteed Mexico an annual delivery of 60,000 acre-feet of water to the head of the Acequia Madre in Juarez (Clark 1975). In years of water shortages, both countries share equally in the shortage. The IBWC has the responsibility for ensuring that the delivery requirements of the treaty are met.

Elephant Butte Dam and Reservoir

Elephant Butte Dam (originally named Engle Dam) is part of the Bureau of Reclamation (BOR) Rio Grande Project, which was authorized by the Secretary of the Interior on 2 December 1905 (under the provisions of the Reclamation Act of 1902); funds were allocated in 1905 to begin work on the first diversion units (U.S. Bureau of Reclamation 1981). In 1907 Congress appropriated $1 million, the State Department's share for allocation by treaty of 60,000 acre-feet of water annually to Mexico, for construction of Elephant Butte Dam, located 6 km east of Truth or Consequences, New Mexico.

Elephant Butte Dam was completed in 1916 at a cost of about $5 million. At the time it was the world's largest dam, and it created the second largest man-made water impoundment in the world. The original storage capacity was 2,634,800 acre-feet at a spillway crest elevation of 1,343 m with a surface area of 14,780 ha (U.S. Bureau of Reclamation 1981). Storage was reduced by siltation to about 84% of capacity, or 2,220,600 acre-feet, by 1974, and to about 2,065,000 acre-feet, or 78% of original capacity, at present (U.S. Army Corps of Engineers 1989). Elephant Butte Dam is a concrete gravity dam containing 481,300 m^3 of concrete; it is 92 m high and 501 m long including the spillway. Storage operations began in 1915, 1 year before completion. Modifications to the original Elephant Butte Dam included the addition (in 1921) of a spillway channel below the dam (modified in 1947), the addition of a 24,300-kilowatt hydroelectric power plant (1940), and the addition of service outlet deflectors (1944). Elephant Butte Reservoir is managed by the BOR, and water is distributed by the Elephant Butte Irrigation District and the El Paso County Water Improvement District No. 1. The areas irrigated with water from the reservoir are known as the Rio Grande Project.

In 1909 Colorado secured permission to construct several private reservoirs that would provide total storage of 300,000 acre-feet. The last dam was built in 1928. These dams included Continental Reservoir on Clear Creek, Rio Grande Dam on the Rio Grande, La Jara Reservoir on La Jara Creek, Terrace Reservoir on Alamosa Creek, Sanchez Dam on Culebra Creek, and Santa Maria Dam on North Clear Creek.

The Rio Grande Compact

In 1923 the U.S. Congress consented to negotiation of the Rio Grande Compact among Colorado, New Mexico, and Texas, in order to agree on downstream deliveries of Rio Grande water. In 1929, the negotiating parties reached agreement on the "status quo" of river development, and an interim Rio Grande Compact was issued.

The Rio Grande Compact (McClure et al. 1939) is a legal agreement among the Rio Grande Basin States (Colorado, New Mexico, and Texas), intended to allocate the water of the basin above Fort Quitman, Texas, in an equitable and impartial manner. The compact was approved by the states and Congress in 1939. Overseeing the Rio Grande Compact is a board of commissioners composed of the state engineers for New Mexico and Colorado, and a representative from Texas selected by the governor. A nonvoting federal representative appointed by the President of the United States chairs the Rio Grande Compact Commission.

A key element of the compact is the assignment of explicit water delivery obligations by the upstream states to those downstream. Historically, New Mexico and Colorado have been unable to meet those obligations and have been in debt much of the time.

Colorado must meet two delivery schedules in order to supply New Mexico with the required compact water allocation, one for the Rio Grande mainstem and the other for the Conejos River. The inflow gage, or index flow point, for the Conejos River is the Mogote gage; the outflow gage, or delivery point, is the La Sauses gage, which is on the Conejos River just upstream from the confluence with the Rio Grande. The inflow gage for the mainstem is at Del Norte and the outflow gage is at Lobatos.

The upstream inflow gage for New Mexico is the Otowi gage, just downstream from the confluence of the Rio Chama and Rio Grande in New Mexico. The delivery point for New Mexico is Elephant Butte Dam.

All normal reservoir regulation of COE projects in the basin for flood control must be in accordance with Public Law (PL) 86-645 (discussed later); however, temporary deviations to address emergency conditions can be made with the advice and consent of the compact commission. The purpose of this restriction is to ensure that compact deliveries are not impaired or altered by the operation of reservoirs.

The Rio Grande Compact is probably the most important document governing the flow of water through the Rio Grande. Water projects developed on the Rio Grande and tributaries after the compact took effect had to be designed to meet the strict water allocations set forth in the compact. Details concerning these allocations can be found in U.S. Army Corps of Engineers reports (1989).

The Middle Rio Grande Conservancy District

The Middle Rio Grande Conservancy District (MRGCD) was formed in 1925 in response to community pressure concerning the decrease in productive, irrigated farmland and increased flooding along the MRG. Channel aggradation, flooding, and waterlogging of arable lands resulted from Rio Grande water infiltrating the groundwater system of the lower, surrounding floodplains. This resulted in a dramatic decrease in productive farmland, from a possible 50,600 ha in 1880 to about 16,000 ha in 1925 (Nanninga 1982). It is unclear if the reduction in farmable acreage was due to the river or to general economic depression in the 1920's (Wozniak 1987). Regardless of the exact acreage in production and the subsequent decline, there was a definite problem with the river system and its effect on valley farmlands; improvements were needed in irrigation systems, diversions, and flood protection structures. A cooperative community effort led by members of the Albuquerque Chamber of Commerce, Albuquerque Kiwanis, Rotary clubs, and the Board of Realtors in Albuquerque led to the passage of the New Mexico Conservancy Act in 1923 and the subsequent formation of the MRGCD.

From 1925 to 1935 the MRGCD constructed, operated, and maintained four major diversion dams (Cochiti, Angostura, Isleta, and San Acacia), two canal headings, and many miles of drainage canals, river levees, and main irrigation canals (Middle Rio Grande Conservancy District 1980). Angostura, Isleta, and San Acacia diversions were rehabilitated by the BOR between 1955 and 1958. The MRGCD continues to manage the diversions but relies on assistance from the BOR and COE for maintenance and construction. A discussion of the basic irrigation system in use in the MRG is presented in appendix A.

The initial, basic flood-control structures consisted of levees that paralleled the river. The average width of the floodway within the levees was about 450 m and the average levee height was about 2.5 m (U.S. Bureau of Reclamation 1977). From 1951 to 1977 a system of Kellner jetty fields was installed along the MRG to protect levees and to aid in flood control and channel stabilization. The construction and function of the levee system and Kellner jetties are discussed in greater detail in appendix B.

In recognition of continued flooding and sedimentation problems on the MRG, the COE and BOR jointly prepared the "Rio Grande Comprehensive Plan." The COE's portion of the plan provided Jemez Canyon Dam in 1953, Abiquiu Dam and Reservoir in 1963, Galisteo Dam in 1970, and Cochiti Dam and Reservoir in 1973. The system consisting of Abiquiu, Jemez Canyon, Galisteo, and Cochiti dams and the levees along the Rio Grande provides flood control and protection for the MRG valley (Lagasse 1981).

El Vado Reservoir on the Rio Chama was proposed by the MRGCD in 1928. The reservoir was to provide the MRGCD with irrigation and flood control; an agreement with the Department of the Interior provided for irrigation water to also be supplied to six Indian Pueblos in the area (Cochiti, Isleta, Sandia, San Felipe, Santa Ana, and Santo Domingo). Construction of El Vado Dam was completed in 1935, and the dam was rehabilitated in 1954–55. The MRGCD transferred operating responsibility to the BOR in 1956.

El Vado, being a post-Rio Grande Compact reservoir, has restrictions on the release of native waters when New Mexico is in debt to Texas. Water diverted from the San Juan River basin and stored at El Vado is not governed by the compact constraints and can be released from storage for beneficial use in New Mexico (U.S. Army Corps of Engineers 1989).

El Vado dam is a random earthfill structure. It is 47 m high and 415 m long, including the spillway. The reservoir has a capacity of 195,440 acre-feet at a crest elevation of 2,104 m (U.S. Bureau of Reclamation 1961).

In 1937, the National Resources Committee completed the Rio Grande Joint Investigation to evaluate the water resources upstream from Fort Quitman; review past, present, and prospective uses and consumption of water in the basin; and explore the opportunities for conserving and augmenting the water resources by all feasible means. During the Rio Grande Joint Investigation it was determined that water loss occurs to phreatophytes that transpire large quantities of water, yet have little or no monetary value (National Resources Committee 1938).

Flood Control, Diversion Projects, and Public Laws

Caballo Dam

Caballo Dam, located 27 km downstream from Elephant Butte Dam, was authorized in 1933, and construction began in 1936. Caballo Dam was originally part of the Rio Grande Rectification Project to provide flood control in the El Paso-Juarez Valley. Caballo Dam has three purposes: to provide storage for irrigation water; to provide for flood control storage; and to allow year-round electrical power generation at Elephant Butte by providing storage for passed water. Caballo Dam also provides replacement storage lost at Elephant Butte due to siltation.

Caballo Dam is a zoned earthfill structure and is 24 m high and 1,390 m long. The storage capacity is 343,990 acre-feet at a crest elevation of 1,305 m. Caballo Dam is managed by both the BOR and the U.S. Section of the IBWC (in coordination with the Mexico Section of the IBWC); the BOR is responsible for conservation operations, and the IBWC is responsible for flood control operations. Caballo Dam was completed in 1938 and was followed by canalization of the Rio Grande between Elephant Butte and El Paso and completion of the American Diversion Dam and Canal.

Platoro Dam and Reservoir

Platoro Dam and Reservoir, on the Conejos River in Colorado, was authorized in 1940 for conservation and flood control. If necessary, the conservation pool is drained in spring to provide space for snowmelt runoff and flood control. Construction began in 1949 and was completed in 1951. Platoro Reservoir has a storage capacity of 59,570 acre-feet at a spillway crest elevation of 3,058 m. The dam is a zoned earthfill type and is 40 m high and 465 m long, including the spillway and a 180-m dike. First storage in the reservoir began in July 1950. The BOR manages the facility and coordinates with the state of Colorado on water rights and the COE on flood-control matters. Platoro is a post-Rio Grande Compact reservoir and must comply with the conditions of the Rio Grande Compact.

Flood Control Act of 1948

The Flood Control Act of 1948 (PL 80–858) provided authorization for the construction of Jemez Canyon Reservoir and the low-flow conveyance channel from San Acacia to Elephant Butte Reservoir. Public Law 80-858 also authorized the BOR to maintain the channel of the Rio Grande from Velarde to Caballo Reservoir to accommodate flows of about 5,000 cfs.

The low-flow conveyance channel. The low-flow conveyance channel is used to transfer water through its 82-km length more efficiently during periods of low flow, which minimizes water losses to infiltration and phreatophytes. The low-flow conveyance channel is normally operated to convey the entire flow in the Rio Grande up to about 2,000 cfs; when flows exceed about 2,000 cfs, the remainder is carried by the natural channel. Water is also allowed to flow in the natural channel when the silt load is high.

Jemez Canyon Dam and Reservoir. Jemez Canyon Reservoir on the Jemez River was authorized in 1948 to provide flood and sediment control in the MRG. The reservoir is formed by an earthfill dam that was completed in 1953. The reservoir has a capacity of 102,700 acre-feet at a crest elevation of 1,595 m. The original plan for reservoir operation was to desilt all flow above 30 cfs by storage for 1 day before release to the Rio Grande and for possible detention during flood stage on the Rio Grande. Maintenance and operation of Jemez Canyon Dam and Reservoir are conducted by the COE.

Flood Control Act of 1960

The Flood Control Act of 14 July 1960 (PL 86–645) contains the criteria governing operation of the four Middle Rio Grande Project flood control reservoirs: Jemez Canyon, Abiquiu, Cochiti, and Galisteo. Portions of the operating criteria include the following.

- Jemez Canyon, Abiquiu, Cochiti, and Galisteo reservoirs are to be operated expressly for flood control and sediment control.
- The outflow from Cochiti Reservoir during each spring flood and thereafter will be at the maximum rate of flow that can be carried at the time in the channel of the Rio Grande through the middle valley without causing flooding of areas protected by levees or unreasonable damage to channel protective works.
- Whenever during the months of July, August, September, and October there is more than 212,000 acre-feet of storage available for regulation of summer floods and the inflow to Cochiti Reservoir (exclusive of that portion of the inflow derived from upstream flood-control storage) is less than 1,500 cfs, no water will be withdrawn from storage in Cochiti Reservoir and the inflow derived from upstream flood-control storage will be retained in Cochiti Reservoir.
- Releases of water from Galisteo Reservoir and Jemez Canyon Reservoir during July, August, September, and October will be limited to the amounts necessary to provide adequate capacity for control of subsequent summer floods; such releases when made in these months, or thereafter, will be at the maxi-

mum rate practicable under the conditions at the time.

- All reservoirs will be evacuated completely on or before 31 March of each year.
- When estimates of anticipated streamflow made by appropriate agencies of the federal government indicate that the operation of reservoirs constructed as a part of the Middle Rio Grande Project may affect the benefits accruing to New Mexico or Colorado under the provisions of the eighth unnumbered paragraph of Article VI of the Rio Grande Compact, releases from such reservoirs shall be regulated to produce a flow of 10,000 cfs at Albuquerque, or such greater or lesser rate as may be determined by the chief of engineers at the time to be the maximum safe flow, whenever such operation shall be requested by the Rio Grande Compact commissioner for New Mexico or the commissioner for Colorado, or both, in writing before commencement of such operation.
- No departure from the foregoing operation schedule will be made except with the advice and consent of the Rio Grande Compact Commission.
- Whenever the COE determines that an emergency exists affecting the safety of major structures or endangering life and shall so advise the Rio Grande Compact Commission in writing, these rules of operation may be suspended during the period of, and to the extent required by, such emergency (U.S. Army Corps of Engineers 1989).

Galisteo Dam and Reservoir

Galisteo Creek formerly had a long history of violent flash-floods that delivered large volumes of sediment to the Rio Grande. The large volumes of sediment discharged by Galisteo Creek into the Rio Grande were sufficient to cause altered sediment transport capabilities and changes in channel pattern of the Rio Grande upstream and downstream of the discharge point (Lagasse 1980).

Galisteo Dam was authorized by the Flood Control Act of 1960 and is a dry-stream flood control facility constructed for the purposes of sediment and flood control. The dam and reservoir effectively eliminate large sediment discharges from Galisteo Creek into the Rio Grande. The dam is an earthfill structure and was completed in October 1970. The reservoir has a capacity of 88,900 acre-feet, but is empty most of the time. Management of the facility is by the COE.

Cochiti Dam and Reservoir

Cochiti Reservoir was authorized by the Flood Control Act of 1960. Cochiti Dam is located on the Middle Rio Grande in Sandoval County in north-central New Mexico near the confluence of the Cañada de Cochiti, the Santa Fe River, and the Rio Grande, just downstream from White Rock Canyon. Cochiti Dam, as originally authorized, was to have been constructed only for flood and sediment control on the main stem of the Rio Grande. Because a previously existing irrigation diversion structure was eliminated by the dam, Cochiti Dam also serves as a delivery point for irrigation waters for downstream Indian Pueblos and non-Indian agricultural lands.

Subsequent to authorization of Cochiti Dam for flood control, the BOR was authorized by the Act of 13 June 1962 (PL 87-483) to construct the San Juan-Chama Transmountain Diversion (SJC) Project. The SJC Project makes possible an average annual diversion of about 110,000 acre-feet from the upper tributaries of the San Juan River through the Continental Divide and into the Rio Grande drainage.

Public interests in New Mexico, through their congressional delegations, requested establishment of a permanent pool at Cochiti. By PL 88-293, on 26 March 1964, the 88th Congress authorized the secretary of the interior to make water available from the SJC Project for a permanent pool at the Cochiti Dam site for the development of "fish and wildlife resources, conservation, and recreation purposes." The recreational pool was authorized to be 485 ha (50,000 acre-feet) for initial filling. Annual deliveries of about 5,000 acre-feet of SJC water are required to offset evaporation at Cochiti (estimated to be 5,900 acre-feet annually). As a result of PL 88-293, the Cochiti Dam Project was changed from a flood control project to a multipurpose project, and construction was begun on 11 February 1965 (U.S. Army Corps of Engineers 1974).

Cochiti Dam was completed in November 1973. The dam is a rolled earthfill embankment with a crest length of more than 8 km and a crest height of 76 m above the Rio Grande stream bed. Reservoir capacity is 596,400 acre-feet (based on a 1981 sediment survey). The lake has a surface area of 3,790 ha at the top of the flood-control pool, extends about 32 km upstream, and affects White Rock Canyon, Bandelier National Monument, and vegetation and wildlife. The outlet works include a gated intake structure, a three-barrel conduit, and a terminal stilling-basin structure. Maximum discharge capacity through the conduits at maximum pool stage is 15,000 cfs. A spillway is located on the left abutment at the southern end of the embankment on the Santa Fe River. Above the spillway the Santa Fe River is diverted through a conveyance channel to Cañada de Cochiti and Cochiti Reservoir. Cochiti is operated by the COE.

Cochiti Dam also serves as a delivery point for irrigation water to downstream users. Water is released to the Cochiti Eastside Main Canal on the left bank (east) and to Sili Main Canal on the right bank (west) for irrigation of about 2,430 ha. The irrigation system had been in place many years before authorization of Cochiti Dam.

San Juan–Chama Transmountain Diversion Project

The SJC Project to import water from the San Juan River basin (in the Colorado River basin) was authorized in 1963 under P.L. 87-483. Construction on the project began in 1964 and was completed in 1971. The SJC Project consists of diversion dams, conveyance channels and tunnels, and storage dams on the Rio Chama. Azotea Tunnel conveys Colorado River basin waters diverted from the Rio Blanco (by Blanco Diversion Dam and Blanco Tunnel) and the Navajo and Little Navajo rivers (by Little Oso Diversion Dam and Oso Tunnel) into the Rio Chama drainage basin for storage at Heron Reservoir. The stored diversion water is passed downstream through El Vado Reservoir.

Water diverted from the San Juan River drainage basin and stored at El Vado is not subject to restrictions of the Rio Grande Compact and can thus be released for beneficial use in New Mexico (U.S. Army Corps of Engineers 1989). Complex accounting procedures govern the storage and release of SJC Project water stored in Heron and El Vado reservoirs. Although SJC Project water is not governed by the Rio Grande Compact, the compact places restrictions on the release of water stored in post-compact reservoirs upstream of Elephant Butte Reservoir when project storage of usable water falls below 400,000 acre-feet.

Public Law 87-484 makes possible an average annual diversion of about 110,000 acre-feet of San Juan River basin water into the Rio Grande drainage. The SJC Project can divert a maximum of 270,000 acre-feet in any one year, limited to a total of 1,350,000 acre-feet in any consecutive 10-year period. The imported water is stored and held for release in Heron Reservoir.

The legislation authorizing the SJC Project allowed SJC Project water to be used for municipal, irrigation, domestic, and industrial purposes, and to provide recreation and fish and wildlife benefits. Several entities have contracted with the Department of the Interior for the SJC Project water, including U.S. Department of Energy, city of Albuquerque, MRGCD, Santa Fe Metropolitan Water Board, Española, Taos, Twining, Pojoaque Valley Irrigation District, Los Lunas, and Bernalillo. These contracts total 79,150 acre-feet, and the BOR is executing contracts for the remainder. Some of the SJC Project water is also diverted to maintain the Cochiti recreation pool (to offset evaporation losses). The importation of SJC Project water results in a complex procedure to account for SJC storage, losses, and use in the basin. The accounting procedure is partially used to determine New Mexico's scheduled and actual delivery of water to Elephant Butte under the Rio Grande Compact. Therefore, the annual accounting totals are reviewed by the Rio Grande Compact Commission.

Heron Dam and Reservoir

Heron Reservoir, which is part of the SJC Project, was authorized in 1962 and constructed from 1967 to 1971. It is located on Willow Creek at the confluence with the Rio Chama, about 15 km west of Tierra Amarilla, New Mexico. Heron Reservoir is used exclusively to store water diverted from the San Juan River basin, and all native water (i.e., water derived from within the Rio Chama basin) is passed downstream. Carryover storage of contracted water from one year to the next is not permitted, although a waiver of this provision has been granted in recent years, which permitted carryover storage through April of the next year.

Heron Reservoir has a capacity of 399,980 acre-feet at a crest elevation of 2,192 m. The dam is an earthfill structure 84 m high and 372 m long. Heron Reservoir is operated by the BOR.

Abiquiu Dam and Nambe Falls Dam

The Flood Control Acts of 1948 and 1950 (House Document 243, 81st Congress, 1st Session) offered a comprehensive solution to flooding problems and sediment control in the Middle Rio Grande valley. House Document 243 called for construction of three dams: Chiflo on the Rio Grande, Chamita on the Rio Chama, and Jemez Canyon on the Jemez River (discussed previously). The original plan in the Flood Control Act of 1948 called for construction of a high dam called Chamita on the Rio Chama. In the preliminary studies of the area, however, it was determined that a more cost-effective means of obtaining the desired amount of flood protection would be the construction of two dams, one at Abiquiu and a lower dam at the Chamita site. This plan was presented by the COE in a hearing before a subcommittee of the Appropriations Committee during the 1st Session of the 83rd Congress. The request to construct Abiquiu Dam was approved by the Senate Public Works Committee, and $1.5 million was appropriated in FY 1957 to begin construction on Abiquiu Dam. The dam was completed in 1963. The reservoir formed by the earthfill dam has a capacity of 1,201,000 acre-feet at a crest elevation of 1,936 m. In 1981 authorization was extended to include storage of SJC Project water. Dams were never constructed at Chamita and Chiflo.

Nambe Falls Dam on the Rio Nambe north of Santa Fe provides storage for recreation and irrigation in the Pojoaque Valley Irrigation District and the Indian pueblos of San Ildefonso, Nambe, and Pojoaque. The dam was completed in 1976 and is a concrete arch and earthfill structure. The total capacity of the reservoir is 2,020 acre-feet at a crest elevation of 2,081 m.

Albuquerque Metropolitan Arroyo Flood Control Authority (AMAFCA)

Following several large, damaging floods east of the Rio Grande in urban Albuquerque in 1955, 1961, and 1963 (U.S. Army Corps of Engineers 1970), AMAFCA was created in 1963 to address and alleviate the problem of urban flooding from unregulated, ephemeral tributaries (Lambert et al. 1982). AMAFCA constructed a flood control system composed of concrete and earthen retention dams in the upper tributary basin regions near the foot of the Sandia Mountains and concrete lined arroyos that feed to larger channels that ultimately empty into the Rio Grande. AMAFCA is responsible for construction and maintenance of the impoundments and arroyos, but routinely contracts with the COE to advise, construct, and maintain the system. More details concerning AMAFCA are given in appendix B.

Wild and Scenic Rivers Act of 1968

The Wild and Scenic Rivers Act preserves the free-flowing condition of 77 km of the Rio Grande from the Colorado state line through the Rio Grande gorge in northern New Mexico as well as 6 km of the Red River, a northern New Mexico tributary to the Rio Grande.

In 1988, PL 100-633 amended the Wild and Scenic Rivers Act to include about 40 km of the Rio Chama, beginning at the El Vado Ranch launch site downstream to elevation 1,936 m. The reach from elevation 1,936.5 m downstream to elevation 1,915.2 m was designated as a study reach for potential addition to the Wild and Scenic Rivers system. The act also directed the U.S. Bureau of Land Management (BLM), U.S. Forest Service (USFS), and COE to jointly manage the reach from elevation 1,915.2 m to elevation 1,900.4 m. One caveat within PL 100-633 states that "nothing in this Act or the Wild and Scenic Rivers Act shall interfere with the secretary of the army's operation and management of Abiquiu Dam for purposes authorized by Section 5 of PL 97-140 or otherwise authorized before 31 December 1988" (U.S. Army Corps of Engineers 1989).

The Closed Basin Project

The Closed Basin Project in Colorado was authorized by PL 92-514 in 1972. The purpose of PL 92-514 is to help Colorado meet its required deliveries to New Mexico, and to help all three Rio Grande Compact States meet their delivery requirement to Mexico. The Closed Basin Project was justified and funded 100% by the federal government, primarily on the basis of meeting the

1906 treaty requirement to deliver 60,000 acre-feet of water annually to Mexico. Recent legislation that increases the cost ceiling for the project requires some local cost sharing.

The project consists of 170 salvage wells that remove groundwater from the unconfined aquifer in the Closed Basin and discharge the water into the Rio Grande. The water would normally be consumed by evapotranspiration. Approximately 60,000 to 140,000 acre-feet of water will be delivered to the Rio Grande at rates up to 140 cfs when all wells are fully operational.

Public Law 93-493

Public Law 93-493 was passed in 1974 and authorized the Elephant Butte recreation pool, which consists of 50,000 acre-feet of SJC water. The delivery of SJC water was authorized for a 10-year period, which ended in 1985. Since 1985, New Mexico has contracted with the city of Albuquerque for SJC water to maintain the recreation pool.

Public Laws 97-140 and 100-522

Public Laws 97-140 and 100-522 concern SJC water that is authorized for storage in Abiquiu Reservoir. Public Law 97-140 was enacted in 1981 and authorized the secretary of the army to enter into agreements with entities that have contracted for water from the SJC Project. The authorization allows for up to 200,000 acre-feet of SJC water to be stored in Abiquiu Reservoir. The legislation also states that SJC water "shall not interfere with the authorized purposes of the Abiquiu Dam and Reservoir Project and shall include a requirement that each user of storage space shall pay any increase in operation and maintenance costs attributable to the storage of that user's water" (U.S. Army Corps of Engineers 1989).

Public Law 100-522 was passed in 1988 and authorized the storage of up to 200,000 acre-feet of Rio Grande system water in Abiquiu Reservoir, if the space is not required for the storage of SJC water as authorized by PL 97-140. The act also authorized the COE to acquire lands in the reservoir area to ensure proper recreational access. The authorization to store Rio Grande system water is subject to the provisions of the Rio Grande Compact and the resolutions of the compact commission.

The Rio Grande Operating Plan

In 1988 the Committee on Appropriations authorized a $500,000 water resources study (for FY 1988 and FY 1989) by the COE under the Energy and Water Development Appropriations Bill (H.R. Report 100-162, 100th Congress, 1st session, 17 June 1987). The secretary of the army was instructed to prepare a report containing a joint operating plan for the federal reservoir projects in the Rio Grande basin above Fort Quitman, Texas, including Abiquiu Reservoir, Cochiti Reservoir, and Jemez Canyon Reservoir (which are projects operated by the COE), Elephant Butte Reservoir (a paid out reclamation project operated by the BOR), and Caballo Reservoir (a project operated by the BOR, which includes 100,000 acre-feet of flood storage controlled by the IBWC).

The report was prepared in coordination with and with assistance and cooperation from the IBWC, the BOR, and the Rio Grande Compact Commissioners for Colorado, New Mexico, and Texas. The report is to provide recommendations for use of the federal projects for flood control and optimum beneficial uses of the water of the Rio Grande basin above Fort Quitman, Texas.

The Rio Grande Operating Plan is defined by the Rio Grande Compact, treaty obligations with Mexico (1906), reservoir authorizations, and public laws. The federal agencies that manage federal reservoirs have water control manuals and standard operating procedures that give guidance on reservoir operations in accordance with agency policies. Additionally, state laws concerning beneficial water use and water rights play an important role in Rio Grande operations.

Surface Hydrology of the Middle Rio Grande

For purposes of evaluating the effects of flood control and irrigation projects on the biologic community, discharge records must be analyzed for the periods before and after alteration of the natural river. The long history of water developments on the Rio Grande precludes assessment of predevelopment conditions of the river and comparisons with the present system. Thus, it is difficult to determine changes in the biologic community that have occurred due to Rio Grande water developments. Nevertheless, it is useful to evaluate historical discharge conditions on the Rio Grande in the assessment of water development effects on the riparian community.

Rio Grande streamflow in the reach from Velarde to Elephant Butte has two basic sources: spring snowmelt and rains, and summer convective thunderstorms. The efficient movement of this water through the Rio Grande, while maximizing beneficial use, requires careful specification of operating plans and streamflow models. Dependent on the primary interest (e.g., irrigation vs. flood protection) of regulating agencies, and the location of the reach of concern, different hydrologic models might be employed. A single model by itself might be incapable of providing a complete analysis of the flow within a specific reach.

Stage–discharge Relations and Discharge Hydrographs

The data base for discharge on the Rio Grande in the study area is enormous (several hundred thousand records). It is well beyond the scope of this report to present discharge hydrographs for all stations involved in the study area. Mean annual discharge and peak discharge for four stations on the Rio Grande are shown in Figs. 6 and 7.

Stage–discharge relations (i.e., rating curves) are likewise voluminous because of frequent updating necessitated by changes in the natural channel cross section. Some cross sections have experienced numerous changes in cross-sectional area in the past 10 years. The most stable cross sections are those located in bedrock channels in the canyons. Channel cross sections that have experienced the greatest changes are in alluvial channel reaches that are highly mobile. These reaches are most susceptible to change because the river is able to alter the channel planform and cross section during high water and sediment discharges. Thus, stage-discharge relations for channels that alter their cross sections, such as is the case throughout much of the MRG, are transient by nature. Channel cross sections must be resurveyed frequently in some areas in order to develop acceptable rating curves. These types of cross sections yield stage-discharge relations that are difficult to interpret over long periods and have limited utility for long-term prediction of discharge based on river stage. In the lower reaches of the study region changes in cross section, hence rating curves, are mostly a result of the mobile channel, construction of diversions and low-flow conveyance channels, and relocation of gaging stations. In the study area most cross sections are located in alluvial channel reaches; therefore, stage-discharge relations will not be discussed for the MRG. Data are available from the USGS Water Resources Division in Albuquerque, New Mexico.

Since construction of Cochiti Dam, flood damage has been virtually eliminated by regulation of spring flows; however, in the short period since closure of Cochiti (1973), overall average discharge has been greater than before closure (Table 3). Mean annual discharge hydrographs for periods before and after major dam construction are shown in Fig. 6 for Embudo, Otowi, San Felipe, and San Acacia gages. Peak discharge hydrographs for the period of record for Embudo, Otowi, San Felipe, and San Acacia gages are shown in Fig. 7.

These data suggest that the presence of the dam ensures a more consistent flow downstream from Cochiti. The apparent greater discharge may be an artifact of the short length of discharge records since closure of Cochiti Reservoir and spring runoff well above the long-term average runoff before construction of Cochiti Dam. A more regulated discharge below the dam may have an effect on riparian vegetation that relies on seasonal flooding. Also, as noted by Lagasse (1980, 1981), the controlled flows seem to be unable to adequately transport sediment delivered by ephemeral tributaries, which results in localized aggradation and channel instability in reaches affected by tributaries.

Because of the long history of dam construction on the Rio Grande and its tributaries, it is difficult to confidently establish distinct seasonal trends in discharge on the MRG. USGS records for the oldest gages on the MRG typically show the highest discharges from April through August. Summer flooding from high intensity convective thunderstorms essentially has been eliminated on the Rio Grande, with the exception of localized flooding that occurs in the Rio Salado and Rio Puerco drainages and on other smaller tributaries. Localized flooding occurred in the Rio Salado drainage basin

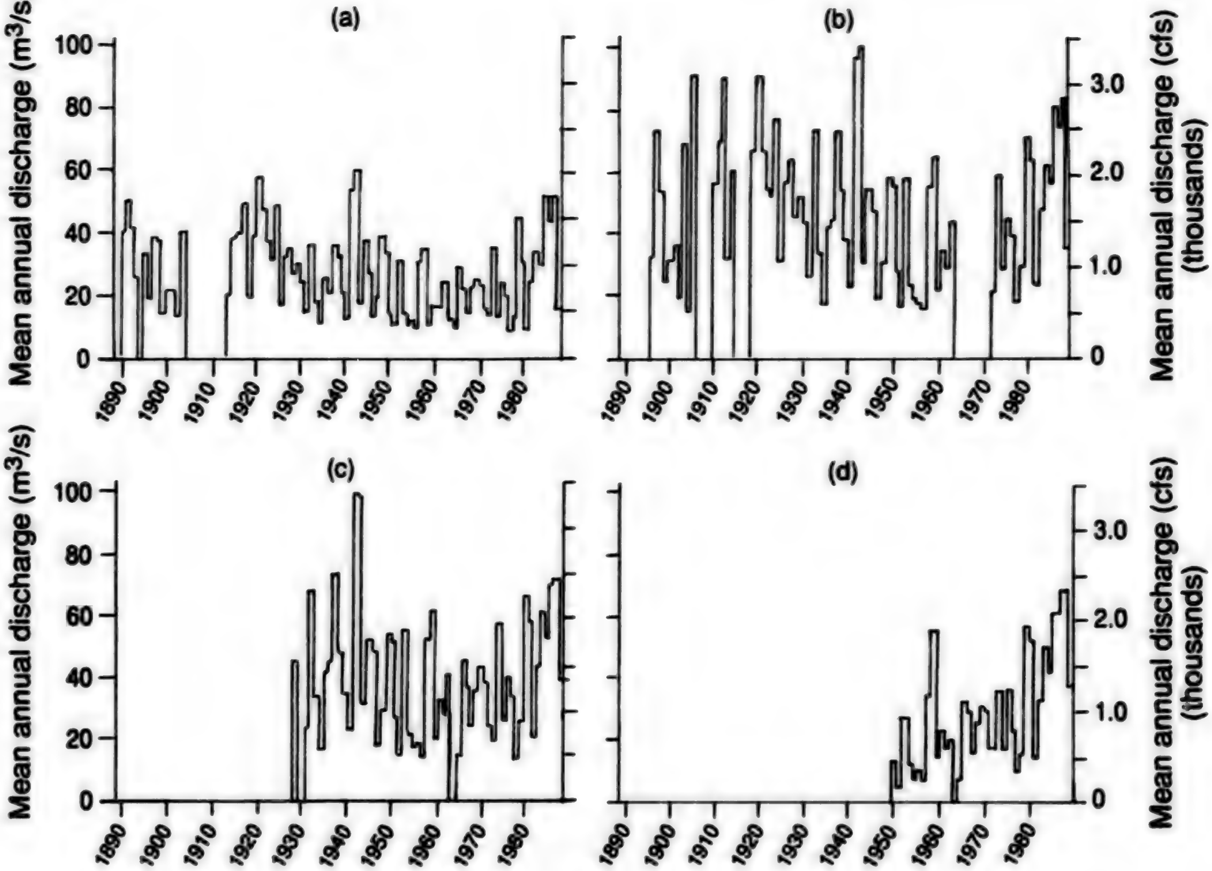


Fig. 6. Hydrographs of mean annual discharge for the Middle Rio Grande at (a) Embudo, (b) Otowi Bridge, (c) San Felipe, and (d) San Acacia. Abiquiu Reservoir was closed in 1963 and Cochiti Reservoir in 1974.

in the summer of 1988 as a result of extreme rainfall, and large volumes of sediment were delivered to the Rio Grande.

Longer discharge records indicate that seasonal variations in discharge were common, and it is probably safe to assume that seasonality in discharge existed in prehistoric time. Figure 8 shows seasonal variation in discharge for the Rio Grande in the years leading up to closure of Cochiti Dam (1971–73) and that the seasonality persists since closure. The major difference between pre- and postclosure of Cochiti Dam is the annual flooding and channel forming discharges that have been controlled by installation of dams, levees, and jetties. An apparent cyclicity in mean annual discharge is present in the Embudo record, which may indicate some degree of long-term regional climatic control on the drainage system. Construction of dams on the Rio Chama and at Cochiti seems to have damped, but not entirely eliminated, the cyclicity recorded in discharge.

Flood Frequency Analyses

Since the installation of dams on the Rio Grande, flooding has been less frequent, although flooding from unregulated tributaries remains a threat. Nevertheless, flood frequency analysis is of interest on the MRG. Flood frequency analysis is required for design of structures such as dams, levees, channels, culverts, and bridges. The analysis computes the probability of a given discharge event based on discharge data at a gaging station. Kite (1977) presents a detailed discussion and derivation of various methods of frequency and risk analyses in hydrology.

A problem still facing hydrologic engineers and researchers is the lack of a reliable data base, in the sense of continuity, information recorded, and

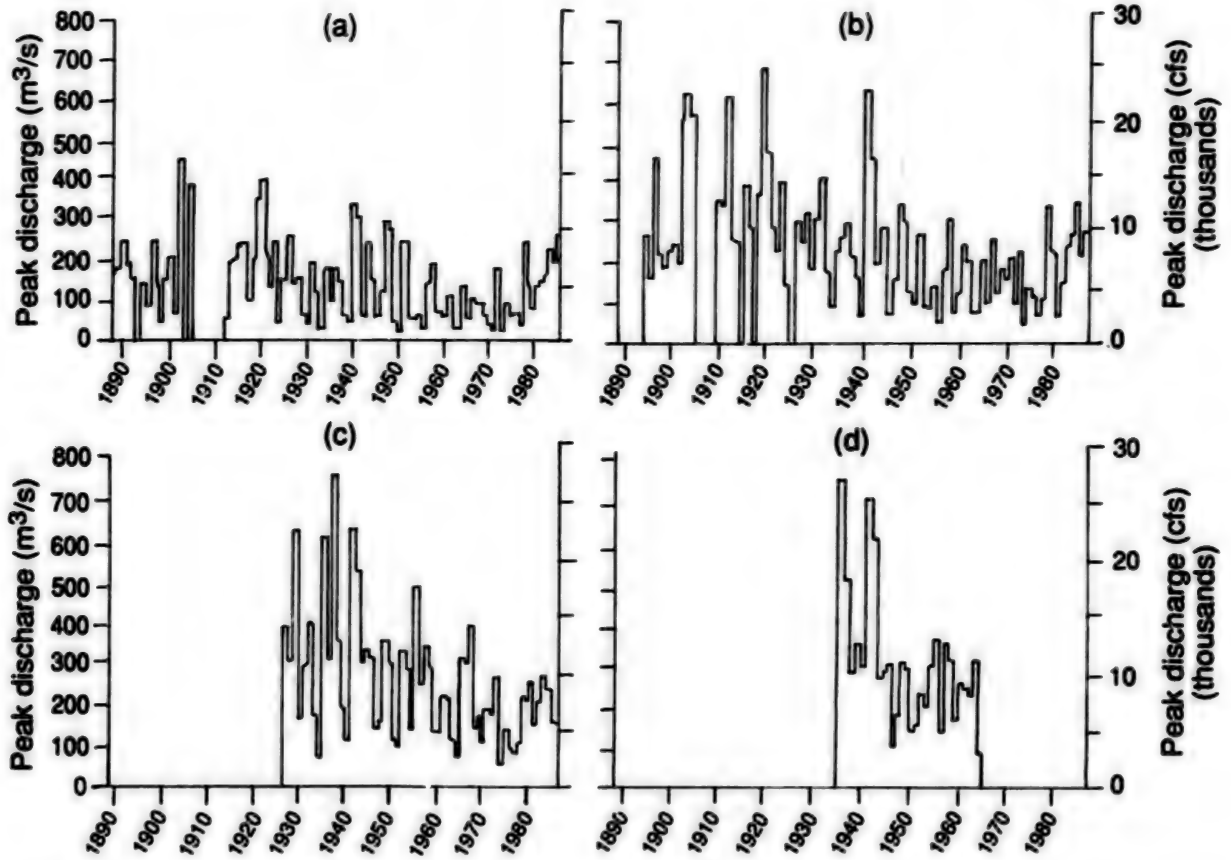


Fig. 7. Hydrographs of peak discharge for the Middle Rio Grande at (a) Embudo, (b) Otowi Bridge, (c) San Felipe, and (d) San Acacia. Abiquiu Reservoir was closed in 1963 and Cochiti Reservoir in 1974.

length of record. New approaches continue to be developed to accommodate the often meager record of historical discharge and flood data. Because of the economics of gaging station installation and maintenance, it is not possible to gage all streams in a drainage basin, especially when many of the streams have discharge for only a few days of the year. However, ephemeral streams often produce some of the more devastating local effects and have the potential to produce large flood events. For purposes of determining flood hazards in the Albuquerque region the COE evaluated the contribution of numerous ungaged ephemeral streams. Waltemeyer (1986) discussed methods and techniques for estimating flood-flow frequency for ungaged streams, which can be critical for proper design in certain reaches of the Rio Grande, such as near Albuquerque and Socorro.

The 100-year flood is often used in engineering design. Engineering designs are typically based on historical discharge records. Quite often discharge records are for relatively short periods such that projections are required in order to predict maximum discharge events. Projections are made from hydrologic models based on simulated storm events guided by actual data. Numerous attempts have been made to address this problem. For example, Laursen (1987) explored the meaning of the 100-year flood and important design considerations when planning for floods of given recurrence intervals. Stedinger and Cohn (1987) reviewed the value and utility of historical flood-frequency data given the length and reliability of historical discharge records. Canuti and Moisello (1987) approached the reliability problem by developing methods for estimating peak discharge through records of mean daily discharge. Tasker (1987) also

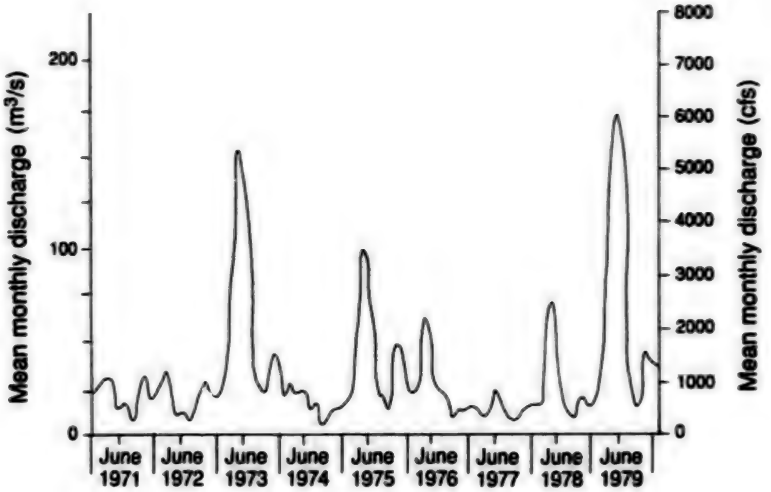


Fig. 8. Hydrograph at San Felipe gage showing seasonal variation in discharge of the Middle Rio Grande (modified from Lagasse 1980).

was concerned with the data base problem and offered improved methods for estimating flood frequency at ungaged sites through regional analysis. A promising method gaining attention in recent years, but not widely used by engineers, uses paleoflood and paleohydrologic data contained in the geologic record. These types of data can be used for developing more accurate, long-term flood-frequency analyses and to aid in engineering design (Baker et al. 1987; Lane 1987). The ability to accurately determine paleoflood frequency from the geologic record would extend the hydrologic record back thousands of years and could provide information giving new meaning to the 100-year flood.

Flood frequency analyses, using log-Pearson Type III frequency distributions, were performed on MRG discharge data for the Embudo, Otowi, San Felipe, and San Marcial gages. Embudo analyses were for the entire period of record (1889-1988). The remaining gages were analyzed for periods before and after construction of Cochiti Dam. Frequency analyses for the four stations produced similar results both before and after regulation by dams. The most apparent trend was that the highest frequency events (i.e., average discharge events) were larger after construction of Cochiti Dam than before. This trend is also apparent in the long-term average discharge for the same stations. At San Marcial, a decrease in flow through the floodway occurred in the 10 years before construction of Cochiti Dam. This may coincide with development of the low-flow conveyance channel. Since construction of the low-flow conveyance channel and Cochiti Dam, discharge through the Rio Grande floodway at San Marcial has been of greater magnitude and duration.

The reasons for these increases since dam construction are not entirely clear. The U.S. Army Corps of Engineers (1989) indicated that spring runoff in the past decade has been above normal, and this may bias the short discharge record since closure of Cochiti. A comparison of the average discharges at a gage for different time periods indicates that large discharge events can weight the average and also produce a somewhat biased result.

Hydrologic Models in Use on the Rio Grande

Hydrologic models are critical for developing operating plans for the Rio Grande. The most common hydrologic methods in use throughout the United States are those developed by the COE Hydrologic Engineering Center (HEC) at Davis, California. A very good overview of the HEC models is given by Feldman (1981). Individual treatments of some HEC models are presented by Henderson (1966), Viessman et al. (1977), Mutreja (1986), and Bedient and Huber (1988).

The Puls and Muskingum methods are the most frequently employed hydrologic flood routing techniques for reservoirs and channels. Both methods are used in the COE HEC-1 model for streamflow routing. The Muskingum method describes the outflow from a reach in one time interval as a linear function of weighted discharges of the previous time intervals (Feldman 1981). The coefficients are determined from prism and wedge storage of the valley routing reach. The Muskingum parameters (time constant K, wedge size x, and number of subreaches) can be derived directly from historical streamflows. The method produces good results for streams with small or no floodplains (valley storage) where there is a linear relation between storage and weighted discharge. Most typical applications use the Muskingum method of flood routing upstream, where floodplains are less-developed, and a storage routing method, such as the Puls or modified Puls, in downstream reaches characterized by larger floodplains.

The HEC models are widely used in floodplain management studies (HEC–1), flood-control investigations (HEC–1, HEC–5), and multipurpose, multiple-reservoir water resources systems simulations (HEC–5). In addition to streamflow routing models, HEC has developed numerous computer programs for evaluating many aspects of watersheds, including (1) rainfall and snowmelt for subbasins, (2) unit hydrographs, (3) streamflow routing optimizations, (4) HEC–2 water surface profile computations, (5) various reservoir capacity, spillway ratings, and reservoir yields, (6) monthly streamflow simulations (HEC–4), (7) flood flow frequency analyses, (8) regional frequency computations (Log-Pearson Type III), (9) water quality, (10) stream and reservoir sedimentation, and (11) expected flood damage (Feldman 1981).

HEC–1 and HEC–5 are the models most frequently used on the Rio Grande for simulating streamflow conditions for purposes of floodplain management and flood damage estimates. The COE uses HEC–1 for evaluating flood flows generated in small, uncontrolled tributaries along the Middle Rio Grande (U.S. Army Corps of Engineers 1986). HEC–5 functions in a manner similar to HEC–1 except that reservoir storage is a primary consideration.

The HEC–1 model uses the Muskingum and modified Puls methods to determine streamflow anywhere in a drainage basin. Basic data requirements of HEC–1 are precipitation data for as many subbasins as possible in order to construct the unit hydrograph from which runoff can be estimated, interception and infiltration data, surface runoff from gaging data, baseflow, and channel routing. Gages are assumed to be outlets and represent the beginning and end of routing reaches. Storms may also be simulated to represent extreme conditions. Snowfall and snowmelt are also incorporated into the model. The watershed simulation is accomplished in a converging tree network, as illustrated in Fig. 9 for the Rio Grande.

HEC–5 was used by the U.S. Army Corps of Engineers (1989) in development of operating alternatives during its reevaluation of the Rio Grande Operating Plan. In preparation for use of the HEC–5 model a computer input file is generated containing information on (1) the physical and operational characteristics of each reservoir, (2) diversion and maximum and minimum flow requirements at each river control point, and (3) the interrelations between reservoirs and control points. The resulting computer model is used to simulate the response of the reservoir system under different streamflow situations or with modification of the system, such as transferring conservation storage from one reservoir to another (U.S. Army Corps of Engineers 1980). Flood damage was not accurately depicted in the 1989 COE study owing to exclusion of rainfall and snowmelt simulations from the HEC–5 model.

Geomorphic Response of the Middle Rio Grande

Fluvial Responses to Changing Sediment and Water Discharge

The fluvial system is a dynamic geomorphic component of the natural landscape. When changes occur in the physical parameters of the fluvial system, such as stream slope, sinuosity, and water and sediment discharge, the river attempts to adjust (Schumm 1977). Fluvial systems by nature attempt to maintain a condition of dynamic equilibrium, or energy balance, whereby the discharge of a river is in balance with its sediment load. For a given discharge a stream is capable of transporting a particular volume of sediment. If a decrease in available sediment occurs because of trapping in

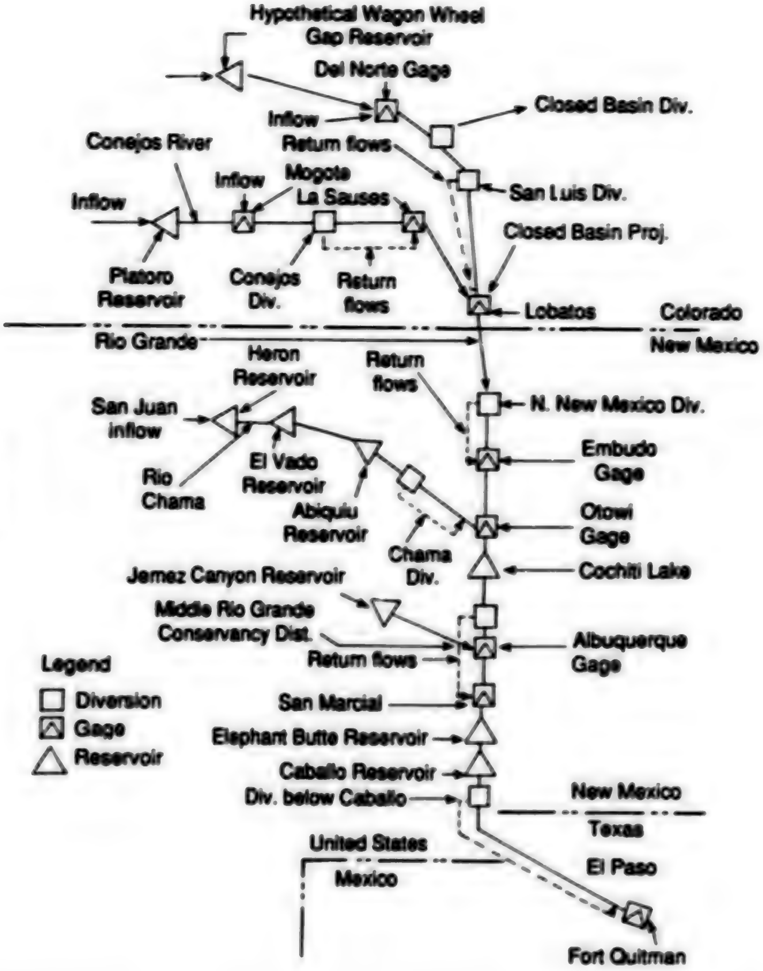


Fig. 9. River network diagram showing flood routing for purposes of developing Rio Grande basin hydrologic model (U.S. Army Corps of Engineers 1989).

reservoirs, a river will tend to erode its channel and banks, thereby incising its bed. An increase in sediment (or decrease in water) will initially force the river to respond by deposition of the sediment load, aggradation, reduction in channel slope, and changes in stream patterns (e.g., meandering to braided). These changes will eventually be followed by incision and additional changes in gradient and channel pattern as the river strives to attain a condition of dynamic equilibrium. These altered river conditions can influence channel water losses, shallow groundwater levels, groundwater flow directions, and riparian vegetation communities. Thus, when streamflow becomes regulated by dams several physical components of the fluvial system must adjust to new sediment and water discharge conditions, including sediment delivered by tributaries.

High sediment discharges from the Rio Puerco and the Rio Salado into the Rio Grande are problematic with respect to the alluvial channel of the Rio Grande and effective water delivery through the lower portion of the Rio Grande between Albuquerque and Elephant Butte Reservoir (U.S. Bureau of Reclamation 1977; Middle Rio Grande Conservancy District 1980; U.S. Army Corps of Engineers 1986). Problems associated with high sediment discharges from tributaries include frequent changes in channel pattern from straight or meandering to braided, decrease in channel capacity, aggradation and increase in floodplain area, rising groundwater levels, and establishment of dense stands of phreatophytes that transpire large quantities of water. These conditions caused dramatic losses in water delivery to downstream reservoirs on the Rio Grande.

These losses in water delivery prompted federal agencies to attempt to resolve the problem by maintaining a well-defined channel for the Rio Grande. Projects implemented by the BOR and COE include channelization, straightening, and elimination of "non-beneficial vegetation" (plants with little or no monetary value that transpire large quantities of water) in order to decrease water losses to plants, improve riverside drain functions for irrigated agricultural lands, and minimize water losses to adjacent floodplains. The ultimate goal of these maintenance programs is to deliver water more rapidly and efficiently to destination reservoirs in order to comply with water laws that govern the use and conveyance of Rio Grande water.

A similar problem has existed in the Española Valley due largely to sediment from the Rio Chama; however, with the addition of several dams on the Rio Chama and its tributaries (El Vado and Abiquiu dams on the Rio Chama and Heron Dam on Willow Creek), discharge of water and sediment is regulated, and influences on the main stem are minimal.

Other smaller tributaries such as Galisteo Creek and Jemez River have been regulated since 1953 (Jemez Dam) and 1970 (Galisteo Dam). Before dam construction the tributaries were subject to occasional high-intensity flooding that contributed high water and sediment discharges to the main stem Rio Grande. Sediment from these two tributaries was formerly an important factor influencing the character of the Rio Grande in the Albuquerque–Belen reach. Sediment from these drainages contributed to aggradation of the Rio Grande, which resulted in perching of the Rio Grande above the surrounding floodplain; the probability of flooding of downtown Albuquerque, situated on the floodplain, was increased by this continued aggradation.

Despite flood and sediment control structures on the major tributaries, about 2,600 km^2 of nonregulated tributary basins in the Albuquerque–Belen region continue to discharge large volumes of sediment and water into the Rio Grande during large rainfall events. These discharges of sediment produce small, persistent deltas at their confluences with the Rio Grande. A reduced channel-forming peak discharge, due to Cochiti Dam, is generally insufficient to remove the deltas, and changes in the river planform are documented to occur both upstream and downstream from the sediment source (Lagasse 1980).

Influence of Tectonics on River Behavior

Active tectonics can exert dramatic influence on the fluvial system. Tectonic activity (e.g., uplift or warping) can cause changes in channel gradient, channel pattern, sediment transport characteristics, and overall geomorphic evolution of a fluvial system. In the tectonically active Rio Grande Rift, the Rio Grande is affected. Ouchi (1983, 1985) found measurable changes in the natural channel of the Rio Grande due to active tectonic uplift near Socorro, including changes in gradient, sinuosity, and sediment transport characteristics. Ouchi (1983) found that the channel gradient initially decreased upstream from the tectonic disturbance and resulted in changes in flow characteristics and sediment transport ability of the river. These changes occurred in the upstream reach as well as downstream from the tectonic disturbance. These studies indicate that, given active tectonism within the Rio Grande Rift, changes in the behavior and pattern of the Rio Grande can be expected to occur through time independent of changes that might be caused by human activity.

Effects of Dam Construction on the Middle Rio Grande

Studies on the effects of dams on the fluvial geomorphology of the Rio Grande began in the early part of the twentieth century. Flock (1931) and the International Boundary and Water Commission (1932) conducted studies of changes in the regime of the Rio Grande for the years 1916–32, following closure of Elephant Butte Dam. These studies provided the initiative for later studies by Lagasse (1980) on the effects of Cochiti Dam on the MRG. Nordin (1964) and Nordin and Beverage (1965) produced a detailed review of the hydraulic characteristics of the Rio Grande before construction of Cochiti Dam. Woodson and Martin (1963) gave an excellent summary of the effects of the Rio Grande Comprehensive Plan on river regime through the MRG.

The studies by Flock (1931) and the International Boundary and Water Commission (1932) identified two main sources of sediment that were available for fluvial transport after closure of Elephant Butte: the river bed, subject to scour by the clear waters released by Elephant Butte Dam, and sediment derived from tributaries. River scour in the first 15 years was about 0.6 m and extended 160 km downstream from Elephant Butte through the Mesilla Dam reach. Sediment entering the Rio Grande from tributaries formed small deltas. These deltas caused localized channel migration or shifting because of the low magnitude and short duration of reservoir releases, which were incapable of effectively transporting sediment. In canyon reaches, the small tributary deltas partially dam the reach and form local base-level conditions, which results in backwaters above, and rapids over, tributary deltas. A gravel armor on the channel bottom is formed in some reaches where the Rio Grande is capable of transporting only the sand fraction supplied by tributaries; the gravel fraction remains behind as an armor on the channel bed.

Before Cochiti Dam construction, the Rio Grande from Cochiti to San Felipe consisted of many braided channels separated by bars and islands composed of coarse gravel and cobbles. The active river bed was composed of sand at low discharges and sand and gravel at higher flows. Downstream from the confluence of the Jemez River, the Rio Grande was a sand-bed stream. The dominant channel-forming discharge, which can balance sediment input and effective sediment transport, was in the range of 6,000 cfs for the pre-Cochiti River (Lagasse 1981).

Schumm (1977) found that during flume experiments a small fraction of the bed material, perhaps the coarsest 1%, can control the behavior and morphology of an alluvial channel by development of a gravel armor layer on the channel bed. Lagasse (1980) studied the MRG before and after closure of Cochiti Dam to assess the effects of sediment reduction on river characteristics. Studies by Flock (1931) and the International Boundary and Water Commission (1932) of the behavior of the Rio Grande immediately downstream of Elephant Butte provided Lagasse (1980) with important interpretive keys for evaluating the effects of Cochiti Dam.

Through quantitative and qualitative studies of river planform, cross-section, and sediment particle size data, Lagasse (1980, 1981) determined that altered sediment load characteristics due to construction of Cochiti Dam have profound effects on the physical nature of the Rio Grande channel. Initial degradation of the channel occurs until an armor of gravel is established on the channel bottom, effectively locking the channel in position and creating a stable condition immediately downstream from the dam. Farther downstream, however, the regulated discharge from Cochiti Dam is insufficient to transport sediment supplied to the main stem by small, unregulated tributaries, resulting in unstable channel configurations (e.g., meandering and changes in channel cross-section) and continued aggradation in certain reaches. The net result is that small unregulated tributaries influence the behavior of the Rio Grande with respect to channel planform, channel cross section, sediment transport, aggradation, and stability.

The ability of small tributaries to affect the Rio Grande channel was due to the reduction in Rio Grande flows below the channel-forming discharge (6,000 cfs). Before closure of Cochiti Dam, average discharge at San Felipe, 24 km downstream from Cochiti Dam, was 1,374 cfs; postclosure the average discharge has been 1,626 cfs. The apparent increase in average downstream discharge through the San Felipe gage since dam closure may be misleading and the implications of this difference in discharge are not immediately obvious. Since closure of Cochiti Dam there has been more consistency in flow of the Rio Grande, and the frequency of large, seasonal flood events has been reduced. Since 1979, 8 of 10 years have produced runoff well above the 20- to 25-year average (200% to 300% of normal; U.S. Army Corps of Engineers 1989), with corresponding increases in discharge. Dam construction has reduced or damped long-term cycles in flow (due to climatic fluctuations), although the cyclicity has not been entirely eliminated.

The elimination of channel-forming discharges and flooding by emplacement of Cochiti Dam has implications for sediment transport and river behavior, as noted previously. Riparian species may also be affected by absence of seasonal floodwater that provides necessary conditions for germination, establishment, and maintenance. Because Cochiti Dam has been in existence for less than 20 years, long-term effects on riparian vegetation and associated faunal communities may not yet be apparent.

Effects on the Rio Grande Upstream From Elephant Butte Reservoir

The effects of dams and reservoirs are not restricted to the reaches downstream from a dam. Obvious changes occur within the reservoir itself as deposition occurs. The reservoir also constitutes a new base level for the upstream reach of the river. A base-level rise created by a reservoir results in a decrease in the slope of the upstream reach and corresponding changes in the fluvial geomorphology and hydraulic geometry.

Siltation and loss of water to the channel are two major effects resulting from the creation of Elephant Butte Reservoir. A major upstream effect of Elephant Butte Reservoir occurred near San Marcial, where the Rio Grande has formed a delta at the head of the reservoir. Artificial base-level conditions created by the reservoir resulted in a reduced river slope upstream that was accompanied by decreases in flow velocity and sediment transport capability. The result was deposition and formation of a large, fine-grained delta, which resulted in development of a system of anastomosing channels, loss of a single, distinct channel, and encroachment and establishment of thick stands of riparian vegetation.

Losses of water to riparian vegetation and infiltration to the channel and deltaic sediments resulted in a decrease in water delivered to Elephant Butte. This prompted the BOR to conduct investigations into the operation and maintenance programs for the Rio Grande and Middle Rio Grande projects (U.S. Bureau of Reclamation 1977). Results of these investigations suggested channelization or rectification of the Rio Grande from Velarde to Elephant Butte to eliminate areas designated as "nonbeneficial" uses of water (i.e., riparian vegetation).

Effects of the rectification program on floral and faunal communities outside of the designated floodway are unknown. Only on rare occasions do river waters extend outside of the levee system; the implications are obvious for plant species that depend on seasonal flooding for germination and establishment, although specific effects still are not known.

An additional effect related to sedimentation and river siltation is the accumulation of toxic materials in the sediments. Popp et al. (1983) and Brandvold et al. (1984) conducted studies on the sediments of the Middle Rio Grande near San Marcial and Socorro and at Elephant Butte and Caballo reservoirs in order to evaluate the potential for toxic materials to be transported through the Rio Grande system. They found that substantial quantities of cadmium, mercury, lead, uranium, and pesticides (18 different kinds in concentrations ranging from undetectable to >500 μg/L) are being transported by the Rio Grande and deposited in Elephant Butte Reservoir. These materials are primarily bound to sediment, although an unknown amount of cycling from sediments to the water column occurs in the reservoir.

Groundwater in the Middle Rio Grande Valley

A basic understanding of the surface and subsurface geology of a region is important for understanding the groundwater system. Characteristics of water-bearing units are determined by the geologic history of the units (depositional environment and sediment type) and the geologic structures that influence the distribution of rock units. The depositional environment of geologic rock units is important in determining characteristics of relative hydraulic conductivities, extent, and continuity of water-bearing units (Freeze and Cherry 1979). The contacts between rock units are important for understanding inconsistencies in flow systems. The mineralogy of water-bearing units can affect the chemical quality of water flowing through a unit. The structural geology of an area is important in making correct interpretations of flow systems. For example, a fault may juxtapose rock units with very different hydrologic characteristics, resulting in significant effects on the flow of groundwater. Adjacent fault blocks that have large differences in thickness of permeable sediments also can affect flow systems.

A comprehensive analysis of the groundwater system of the MRG is beyond the scope of this report. Rather than attempt a regional synthesis of existing data, a more general treatment of the

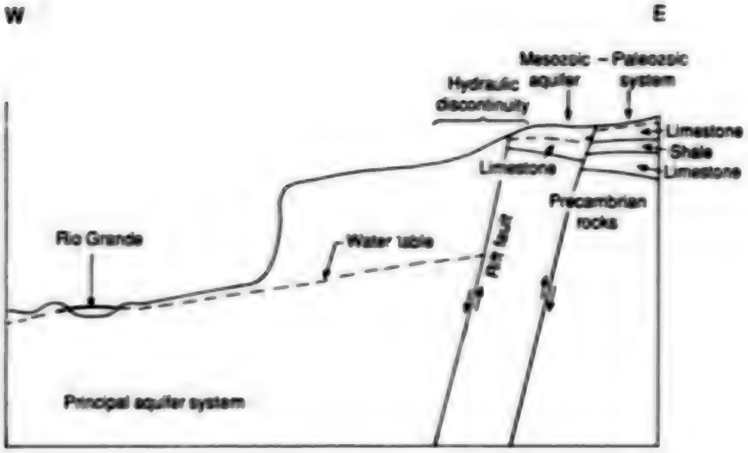


Fig. 10. Generalized hydrologic section for the Middle Rio Grande (Anderholm 1987a).

principal MRG aquifer system is appropriate. Deep aquifer systems recharged by precipitation in the mountains will not be discussed because of (1) their lesser roles in development of the shallow aquifer system, which is more important to the biologic community, and (2) the uncertain relation between alluvial aquifers and deep aquifers (Theis 1938; Caprio 1960; Bjorklund and Maxwell 1961; Kelley 1974; Titus 1980; Anderholm 1987a, 1987b). It is important to determine what changes in groundwater levels have occurred in the Rio Grande valley in response to changes in hydrology of the Rio Grande brought about by dam construction.

Groundwater Flow Within the Middle Rio Grande Valley

The principal aquifer system of the MRG valley is composed of Tertiary sediments of the Santa Fe Group and Quaternary deposits. Both groups of sediments are the main rift-filling sediments, consisting dominantly of gravels, sands, silts, and clays (Lambert 1968). The exact nature of the principal aquifer is not well known in extent or detailed hydrologic characteristics, although the saturated thickness of fresh groundwater may exceed 915 m (U.S. Geological Survey 1972).

Recharge of the principal aquifer comes from two main sources, the margins of the basin and the Rio Grande valley. Paleozoic and Mesozoic sedimentary rock units exposed along the margins of the Rio Grande Rift form local, small aquifer systems that generally flow toward the Rio Grande. Recharge into these small aquifer systems is through infiltration in the bed material of arroyos that intersect the bedrock units of the aquifer system. When these flow systems encounter major rift-bounding faults (Coons and Kelly 1984), which are zones of hydraulic discontinuity, they may connect with and discharge into the principal Tertiary aquifer system (Fig. 10). Thus, the discharge point for one of the small flow systems may be a recharge point for the large principal aquifer (Anderholm 1987a). On a regional scale, many of the small flow systems combine to form a single, large flow system.

The Rio Grande is probably the single greatest source of groundwater in the entire Rio Grande Valley. Groundwater flow in the valley is controlled by the river, conveyance channels, acequias, ditches, laterals, drains, and groundwater inflow from adjacent areas (Fig. 11; Anderholm 1987a, 1987b; Peter 1987). The topographically lower valley areas are sites for aquifer recharge. Shallow alluvial aquifer recharge comes largely from precipitation and runoff that are directed into the valley regions. A small amount of shallow alluvial aquifer recharge is derived from the floodplain. Along the Rio Grande valley the agricultural fields are sloped such that applied irrigation water from an acequia, ditch, or lateral will flow across the field. Return flow from irrigation water infiltrates and recharges the shallow aquifer. As explained earlier, drains were designed and constructed to dis-

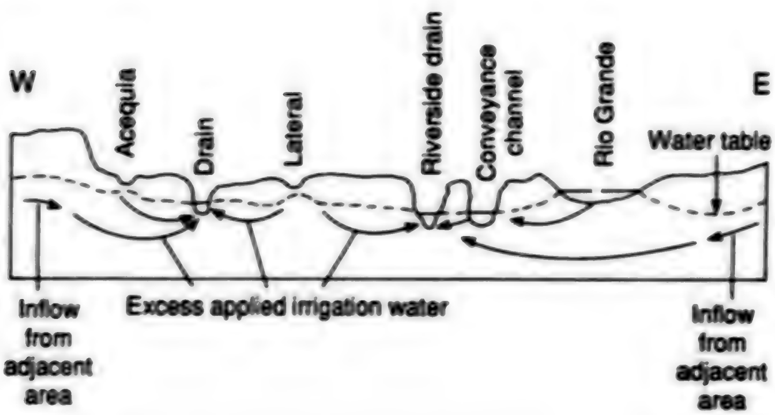

W
Acequia
Drain
Lateral
Riverside drain
Conveyance channel
Rio Grande
E
Water table
Inflow from adjacent area
Excess applied irrigation water
Inflow from adjacent area

Fig. 11. Generalized hydrologic section of an irrigated part of the Middle Rio Grande (Anderholm 1987a).

charge excess water and to prevent waterlogging of the soils, which also promotes flushing the soils of salts that tend to be concentrated by evapotranspiration. The drains also intercept regional groundwater inflow. Conveyance channels and riverside drains are designed to be situated lower than river level, which causes water in the natural channel to infiltrate and flow into the conveyance channel or riverside drains.

Thus, drains are the major factor controlling groundwater levels in the Rio Grande valley (Theis 1938; Anderholm 1987a; Peter 1987). An increase in return flow from irrigation water causes increases in drain flow and small increases in groundwater levels. Groundwater withdrawals for irrigation or domestic use are quickly replaced by return flow irrigation water, regional groundwater inflow, and infiltration of surface water from acequias, ditches, laterals, the river, riverside drains, conveyance channels, or drains. If drains remain unchanged with respect to altitude and spatial configuration, large decreases in groundwater levels in the valley can occur only if groundwater withdrawals exceed the rate of infiltration of return flow from irrigation water, infiltration of surface water, and inflow of regional groundwater.

Groundwater Studies in the Middle Rio Grande

Groundwater studies along the Rio Grande valley are numerous and frequently address site-specific problems (see Borton [1972, 1978, 1980, 1983] for bibliography of groundwater studies in New Mexico) such as groundwater levels (Busch and Hudson 1968, 1969, 1970; Hudson 1971, 1974, 1975a, 1975b; Hudson and Borton 1974), groundwater flow direction (Kues 1986; Peter 1987), groundwater quality (Popp et al. 1983; Brandvold et al 1984; Anderholm 1987a, 1987b), and groundwater resources and uses (Spiegel 1955; Titus 1963; Hale et al. 1965; U.S. Army Corps of Engineers 1979; Kelly 1982). Numerous studies on groundwater contamination from toxic waste and hydrocarbons have been conducted by the New Mexico Environmental Improvement Division (Environmental Improvement Division 1982) in Santa Fe, the New Mexico Water Resources Institute in Las Cruces, and several private consulting firms in the area.

There were many early studies of surface water and shallow groundwater interactions in the Socorro area (Yeo 1928; Bloodgood 1930; Debler 1932), but modern studies relating groundwater changes to the Rio Grande are few and still preliminary. Nickerson (1989) investigated relations of groundwater levels and river stage in the Mesilla Basin downstream from Elephant Butte. Goetz and Shelton (1990) are investigating changes in groundwater levels in the Albuquerque area over a 30-year span. Results are not final, but there seems to be a lack of consistency in groundwater levels through time and a lack of association between river stage and groundwater levels. A short-term study by Peter (1987) on groundwater flow and shallow aquifer properties indicated that groundwater levels fluctuate on a seasonal basis. Groundwater levels are lower during summer months when irrigation and groundwater withdrawals are greater, and higher during winter months. Groundwater levels also seem to be lower near drains and local sources of withdrawal such as municipal water supplies and large irrigation wells.

Groundwater Quality

Groundwater quality along the Rio Grande was first studied in the Socorro region by Mauger (1932), who investigated the chemical quality of groundwater in the area. Bjorklund and Maxwell (1961) and Wilson et al. (1977) recognized the poor quality of shallow (<30 m deep) groundwater in the Albuquerque region, which was attributed to mineralization caused by phreatophyte vegetation and seepage of irrigation waters into wells.

Not unexpectedly, shallow groundwater quality may be greatly affected by intense irrigation of the floodplain, especially in cases where facies of the floodplain sediments are characterized by low hydraulic conductivities and groundwater circulation is slow. Groundwater withdrawals in the valley for domestic or irrigation uses are generally quickly replaced by return flow from irrigation waters, regional ground-water inflow, or infiltration of surface water from acequias, ditches, laterals, the river, riverside drains, conveyance channels, and drains (Anderholm 1987a). Irrigation water may also affect river water quality. Irrigation return flow often contains high concentrations of dissolved salts, which can affect water quality downstream.

McQuillan (1982) presented an overview of pollution of the Rio Grande valley-fill aquifer, indicating contamination of the shallow groundwater system by nitrates and organic compounds such as gasoline and diesel fuels. The Environmental Improvement Division (1982) provided an inventory of groundwater pollution and water quality in New Mexico and has numerous ongoing studies in the state at sites with anomalous water quality. Wilson et al. (1977) attributed widespread, generally low-level pollution in the Albuquerque area to numerous on-site septic tanks and leach fields. The findings of these studies are further supported by investigations by Heggen et al. (1979). Additional nitrates are to be expected from agricultural practices and regional groundwater that may transport chemicals from host aquifers in the Paleozoic section. Anderholm (1987b) attempted to show a relation between land-use patterns and effects on the groundwater quality in the Rio Grande valley near Albuquerque, where locally high concentrations of trace elements such as arsenic are present, but the results were inconclusive. In the Socorro region Anderholm (1987a) found high concentrations of chloride in the groundwater. The excessively high chloride concentrations have been attributed to circulation patterns within the principal aquifer system, which bring deep, chloride-enriched waters into contact with the shallow, near-surface aquifer system. Constrictions in the principal aquifer system due to geologic structures create hydraulic discontinuities that may be responsible for the development of anomalous circulation patterns.

Conclusion

The effect of Rio Grande dams on the riparian biologic community is not well understood. Long-term discharge records exist for the Rio Grande, but the long history of streamflow regulation reduces the overall usefulness of discharge data for evaluating changes that may have occurred to the river as a result of water development projects. It seems that mean annual discharge of the Rio Grande has been more consistent, yet slightly greater, since closure of Cochiti Dam. The major problems existing for the riparian biologic system seem to be related to the agricultural history of the Rio Grande valley, which dates back centuries, and associated legislation for control and delivery of Rio Grande water to downstream consumers. The large influx of people into the region in the mid-1800's, added to the existing Indian and Spanish population, increased the demand for water and stretched the limits of the Rio Grande in terms of water delivery and support for plant and animal communities. Diversions of water for irrigation during late summer months, when Rio Grande discharge is lowest, may at times leave the river with little or no flow.

Significant changes in the riparian community were probably under way by the turn of the 19th century. When Congress authorized the Rio Grande Project in 1905, change in the Rio Grande system was accelerated. Since that time the Rio Grande has been converted from an essentially natural stream to a highly modified water storage and conveyance system with extensive flood control structures (Lagasse 1980). More recent changes brought about by the efforts of the COE, BOR, BLM, MRGCD, AMAFCA, Interstate Stream Commission, and local irrigation districts to enhance conveyance and irrigation have probably further affected the riparian ecology. Dams and levees have all but eliminated former seasonal floods that in the past provided nutrients and moisture to the floodplain ecosystem. Former floodplain regions have been converted to productive agricultural lands and, more recently, to urban communities. Irrigation diversions create low-flow conditions, and at times a dry river bed, in much of the reach downstream from Bernalillo. Riverside drains create hydrologic conditions that attract groundwater from the floodplains and prevent natural river losses from invading the floodplain areas. The result is a man-induced change in the river system that has created an altered floodplain ecology different, though perhaps no less viable, from the former natural condition. More stable hydrologic conditions probably exist now, in contrast to former times when seasonal high discharge events and flooding produced dynamic geomorphic changes in the channel and floodplain, but the overall affect of these changes on the riparian community is unknown.

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Appendix A: Diversion Structures and Irrigation System of the Middle Rio Grande

The opportunity to use irrigation waters in the Middle Rio Grande (MRG) depends on two basic factors: the right to irrigation water, and receiving irrigation water. Irrigation rights are regulated by law; many of the laws governing the allocation and distribution of irrigation waters were established in the early 1900's (New Mexico State Board of Water Commissioners 1914). The Middle Rio Grande Conservancy District (MRGCD) is presently responsible for apportioning rights. These laws are not the focus of this discussion.

Diversion structures on the Rio Grande are designed to divert sufficient irrigation waters for agricultural purposes to users within the MRG valley. Diversion projects are valuable along the lower part of the MRG because of important economic concerns associated with agriculture. Irrigation, however, is not without concern to the environment. The greatest effects of irrigation on the hydrology of the MRG are on water quality, groundwater recharge, streamflow in the Rio Grande, and inner floodplain riparian vegetation.

The Middle Rio Grande Conservancy District

There are four separate reaches of the MRGCD with regard to diversions and irrigation systems: Cochiti, Albuquerque, Belen, and Socorro (Fig. A-1). Major irrigation diversion structures on the MRG, from upstream to downstream, include Cochiti Dam, Angostura Diversion Dam, Isleta Diversion Dam, and San Acacia Diversion Dam. Each diversion dam is located within a separate reach of the 233-km MRGCD. The diversion structures are owned and operated by the MRGCD with the exception of Cochiti Dam, which is owned by the U.S. Army Corps of Engineers (COE). The COE and U.S. Bureau of Reclamation (BOR) assist the MRGCD with maintenance and construction of irrigation structures. Considerable rehabilitation work on canals, laterals, drains, and acequias throughout the MRGCD was performed by the BOR between 1953 and 1961.

Outside of the MRGCD, between Velarde and San Ildefonso, more than 1,300 ha of land are irrigated by water taken from the Rio Grande (New Mexico State Engineer 1978). A new irrigation structure serving 600 families in the Española Valley was dedicated in May 1989. Records pertaining to these irrigation districts can be obtained through the U.S. Department of Agriculture, Soil Conservation Service and Agricultural Stabilization and Conservation Service.

The irrigation system in the MRGCD consists of canals and laterals for delivery of irrigation water to farmlands. A system of drains prevents farmlands on the floodplain from waterlogging (i.e., becoming saturated). The drains intercept shallow groundwater flow, consisting largely of return flow from irrigation water down gradient from points of application, and return these waters to the Rio Grande by way of larger riverside drains. The riverside drains are parallel to and outside the Rio Grande levee system and lower than the channel of the Rio Grande. The drains thus receive water infiltrating from the river and conveyance channels, return flow from irrigation water, some regional groundwater inflow, and surface seepage from canals, laterals, ditches, and drains (Middle Rio Grande Conservancy District 1980). Figure A-2 schematically illustrates a typical irrigation system for the MRG.

The MRGCD distribution and drainage system consists of 322 km of canals, 932 km of laterals, and 642 km of open and concrete pipe drains. Diversion structures at Bernardo, San Acacia, and San Marcial divert low Rio Grande flows into low-flow conveyance channels so as to deliver water to Elephant Butte Reservoir with as few losses as possible to nonbeneficial uses.

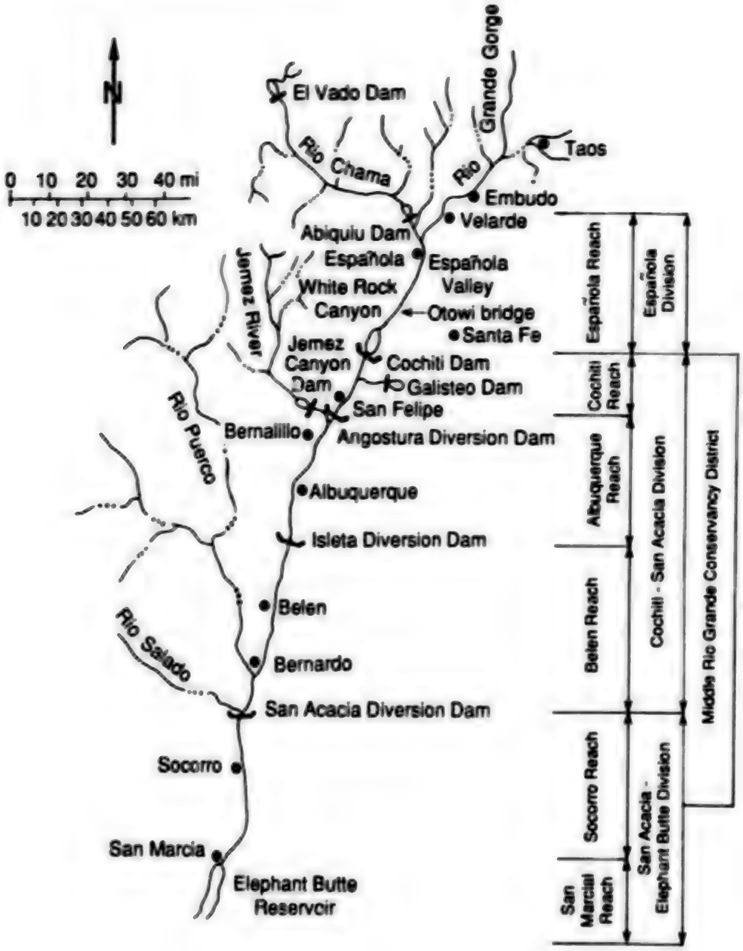

Fig. A-1. Map showing Middle Rio Grande Conservancy District limits, divisions, and reaches for the Middle Rio Grande (U.S. Bureau of Reclamation 1977).

Irrigation Systems of the Middle Rio Grande Conservancy District

The following section describing the irrigation system is taken from the MRGCD Development Statement (1980, pp. IV-7 and IV-8).

Each of the MRGCD reaches derives its water supply from a main canal heading near the river at one of the four diversion dams. The Cochiti and Belen reaches have two such canals, one on each side of the river. The main canals are designed in one of two ways.

- "High-line" canals: These canals run on light supported grade lines without drops. They follow the side hills bordering the valley and, because their grades are much less than the slope of the valley, they become higher above the valley lands in the downstream direction. This makes possible irrigation of much more land; and
- "Low-line" canals: These canals run through the valley floor. They require drops at frequent intervals because the grades required are less than the downstream slope of the valley.

Canals are the largest of the water conveyance channels. They are usually 3 m in bottom width and 1.2–1.8 m in water depth. They convey about 75–650 cfs of water. With the exception of the San Juan Main Canal in Belen, the canals have their headings at one of the diversion dams. Canals usually waste, or empty, into the riverside drains.

The second largest water conveyance channels are called laterals, and they may or may not be prior community ditches. Laterals usually have their headings at a canal. Their channel sections are usually 1.2–1.8 m bottom width with 0.6–1.2 m of water depth. They can convey up to 150 cfs of water. They waste into either an interior drain or riverside drain.

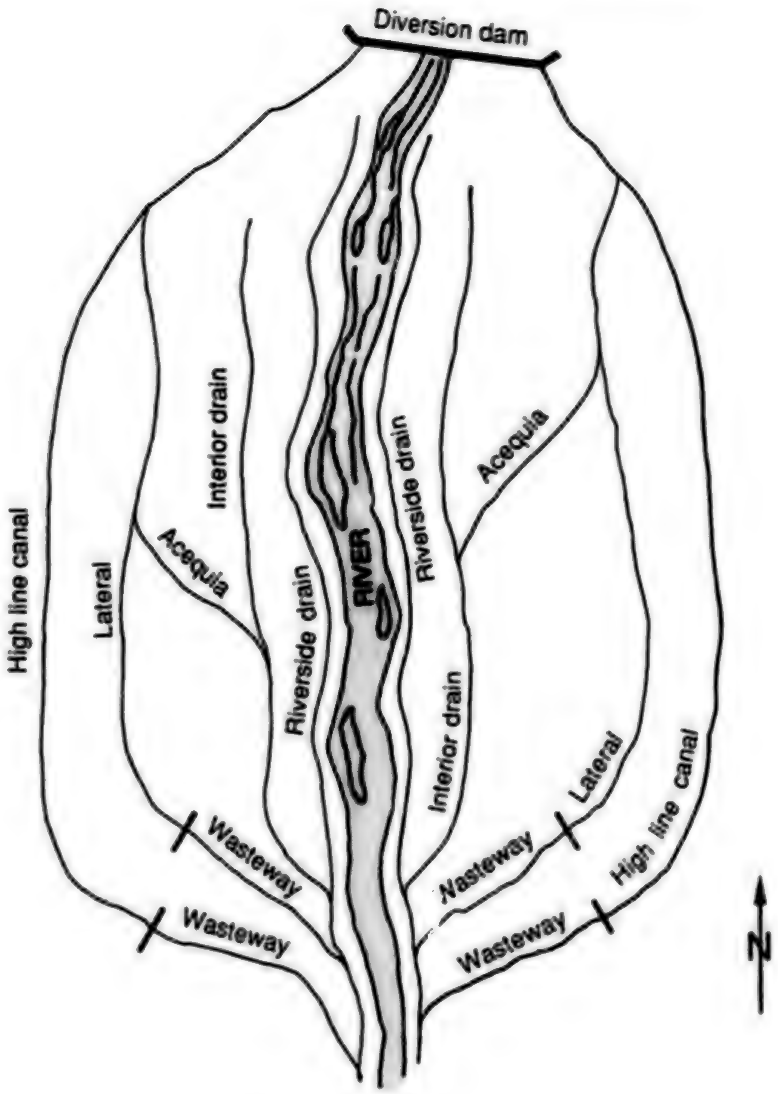

Fig. A-2. Schematic map of an irrigation network on the Middle Rio Grande (U.S. Bureau of Reclamation 1977).

The smallest of the conveyance channels are the community acequias, or ditches. Before district operation, acequias had their headings at the river, usually by rock or brush dams. Today they are usually fed from the laterals. They most commonly are 0.3 m in bottom width and 0.3–0.9 m in water depth, and can convey 15–60 cfs of water. They usually waste into interior drains.

Diversion Structures

Cochiti Dam

About 140 km of laterals and 39 km of drains are contained within the Cochiti reach, which includes the Cochiti Eastside Main and Sili Main canals. Diversions in 1987 were 80,750 acre-feet, or about 5% of total discharge through Cochiti Dam; Cochiti Eastside Main Canal received 54,300 acre-feet, and 26,450 acre-feet were diverted to the Sili Main Canal.

Angostura Diversion Dam

Angostura Diversion Dam serves the Albuquerque reach of the MRGCD. It is located about 8 km upstream from Bernalillo, New Mexico, and diverts water into the Albuquerque Main Canal. Angostura Diversion Dam was completed in 1934 and rehabilitated in 1958. The dam is a concrete wall weir structure 244 m long and 5.2 m high. Headworks for the Albuquerque Main Canal are designed for a diversion capacity of 650 cfs. They consist of a concrete structure with four top-seal radial gates (each 6.1×1.2 m). Water is diverted from the Albuquerque Main Canal into the Corrales Main Canal, the Barr Main Canal, and the Arenal Main Canal, which cross beneath the Rio Grande via siphons. About 233 km of laterals and 228 km of drains are within the Albuquerque reach.

Isleta Diversion Dam

The Isleta Diversion Dam is located about 21 km south of Albuquerque on the Rio Grande, 30 m downstream from the bridge on State Highway 147 at Isleta, and lies within the Belen reach of the MRGCD. The dam was completed in 1934 and is maintained on an annual basis and rehabilitated as funds become available. The dam is a concrete gate structure 205 m long and 6.4 m high. Thirty radial gates (each 6.1×1.5 m) regulate the flow downstream and toward Peralta Main Canal on the left (east) and the Belen Highline Canal on the right (west).

The Peralta Main Canal has a concrete headworks with three top-seal radial gates (each 4.6×1.1 m), and the Belen Highline Canal concrete headworks has four top-seal radial gates (each 6.1×1.1 m). The combined diversion capacity is 1,070 cfs. About 467 km of laterals and 274 km of drains exist in the Belen reach of the MRGCD.

San Acacia Diversion Dam

The San Acacia Diversion Dam is located on the Rio Grande at San Acacia and lies within the Socorro reach of the MRGCD. The dam was completed in 1934 and was rehabilitated in 1957. The dam is a concrete gate structure 213 m long and 5.2 m high; the concrete headworks has three slide gates (each 1.2×1.5 m) to divert water into the Socorro Main Canal on the right bank (west) of the Rio Grande to irrigate of about 3,440 ha. Diversion capacity is 283 cfs. About 109 km of laterals and 111 km of drains exist in the Socorro reach.

U.S. Geological Survey discharge records for the Socorro Main Canal are not completely accurate because of diversion into the Alamillo Acequia and three smaller ditches upstream from the gage; however, sparse data records indicate about 9% of the canal discharge is diverted upstream from the gage. In 1987 the amount of water carried by the Socorro Main Canal was about 92,000 acre-feet, or about 50% of the gaged flow at the Rio Grande Floodway gage at San Acacia. In the 15 years before closure of Cochiti Dam, the average Rio Grande flow and amount diverted (based on the 1987 data) were about 60% lower.

In addition to diversion for irrigation, the San Acacia Diversion Dam diverts water into the San Acacia low-flow conveyance channel, which has a capacity of 2,000 cfs and carries the entire flow of the Rio Grande about 82% of the time. The low-flow conveyance channel is 120 km long, extends to the Narrows of Elephant Butte Reservoir, and ensures that the maximum volume of water passes through the reach, which is known for high water losses to vegetation and sandy floodplain sediments, to Elephant Butte Reservoir.

Appendix B: Additional Flood Control Structures on the Middle Rio Grande

Threat from flooding along the Middle Rio Grande (MRG) is greatly reduced by flood and sediment control structures (dams) on the MRG and tributaries. Levee systems in place along metropolitan areas also provide protection from seasonal flooding. Jetty structures installed along the floodway help reduce erosion of levees and promote establishment of vegetation (thereby increasing the stability of the channel). In the past 25 years attempts have also been made to eliminate or reduce ephemeral tributary flooding in urban areas.

Levee System on the Middle Rio Grande

A levee system was constructed in the 1930's by the Middle Rio Grande Conservancy District (MRGCD) throughout much of the MRG valley to provide flood protection during heavy spring runoff. In 1958 the Albuquerque Division of the MRGCD was reconstructed by the U.S. Army Corps of Engineers (COE) in order to protect the valley in the Albuquerque region from flows up to 42,000 cfs. Operation and maintenance of the Albuquerque levees and their riverside drains were then turned over to the MRGCD (U.S. Army Corps of Engineers 1980, 1989). Construction of Heron, El Vado, Abiquiu, and Cochiti dams greatly reduced the threat of flooding through the MRG; subsequently, the levees upstream and downstream of Albuquerque fell into a state of disrepair. Continued concern over aggradation of the Rio Grande channel and concomitant reduction in capacity prompted reevaluation of the levee system and the protection afforded. A rectification project to clear and maintain a relatively linear floodway was undertaken by the U.S. Bureau of Reclamation (BOR) in the 1970's in order to more efficiently convey water to Elephant Butte and to pass floodwater quickly through the system with minimal water loss and minimal damage to the river channel and floodplain.

Flash-flood threats from unregulated ephemeral drainages (about 2,600 km^2 total) prompted studies that resulted in a recent new phase of rehabilitation of the existing levee system (U.S. Army Corps of Engineers 1986). Studies by the U.S. Army Corps of Engineers (1956, 1959, 1961) in the Socorro region similarly concluded that the major threat from flooding in the area was from unregulated ephemeral tributary drainages. Subsequent projects were initiated to alleviate the situation.

The Levee System

The levee system is located within the irrigated and cultivated floodplain of the Rio Grande where it passes through urban areas of the Española Valley, the Albuquerque–Belen region, and the Socorro area. The floodplain in these areas averages from 1.6 to 9.6 km wide. The existing levees, which average about 2.5 m in height above the river, confine a floodway that has an average width of about 460 m. The floodway along most of the stretch between Española and San Marcial has been straightened and cleared through dredging, chaining, bulldozing, and use of herbicides (U.S. Bureau of Reclamation 1977). The average channel width is about 120–180 m wide and the area between the channel edge and the levees is heavily vegetated (Kinney Inc. 1976). Figure B-1 shows profiles across the inner Rio Grande valley north and south of Albuquerque. Despite the predicted stabilization and degradation of the Rio Grande channel, aggradation has continued, and the river channel is perched above the surrounding floodplain outside the levee system.

Levees were initially constructed from materials dredged from the Rio Grande. Many sections of levees do not meet design criteria for optimal protection because of improper construction and compaction when installed (U.S. Army Corps of Engineers 1978, 1986). Recommendations by the U.S. Army Corps of Engineers (1986) called for rehabili-

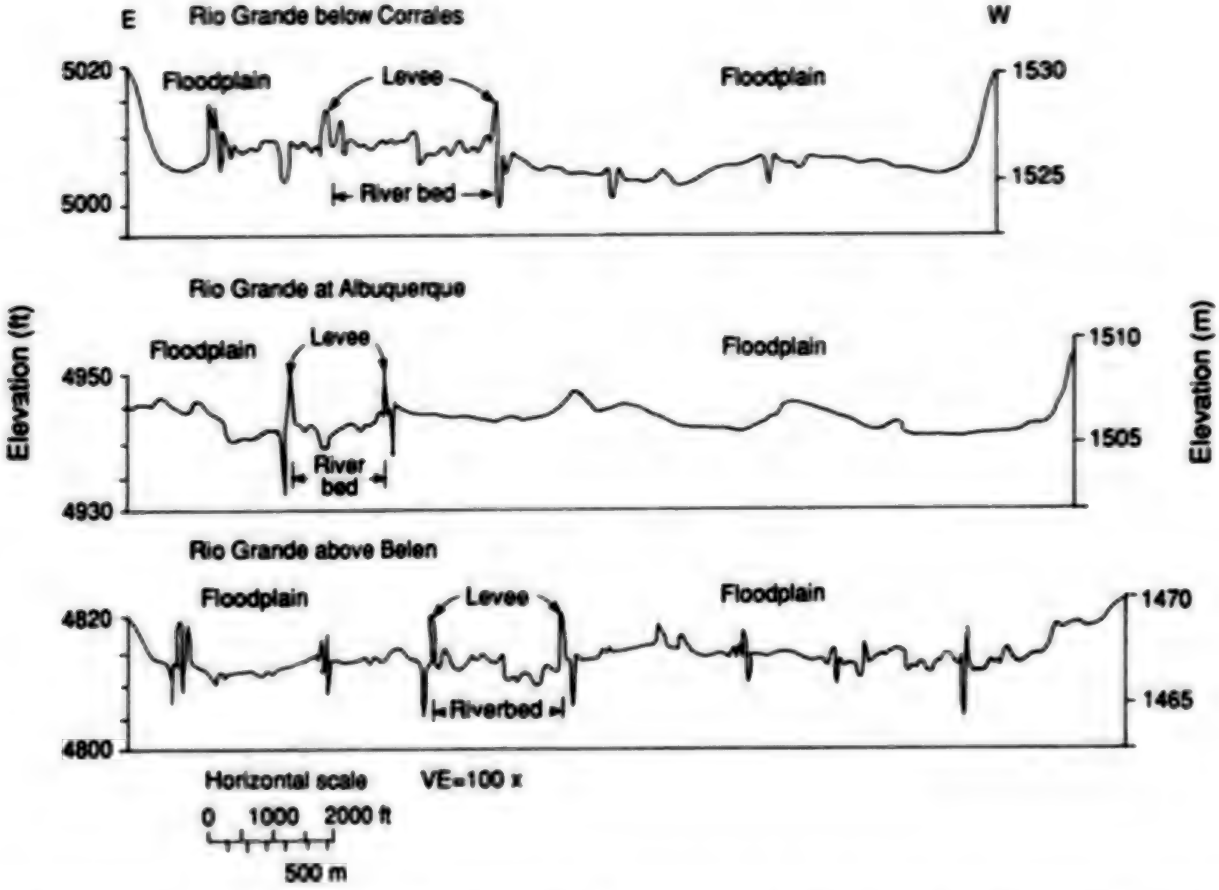

Fig. B-1. Cross-valley topographic profiles showing relation of the Rio Grande to the adjacent floodplain in the Albuquerque region (U.S. Army Corps of Engineers 1980).

tation of 83 km of levees between Corrales and Belen to provide flow capacity of 42,000 cfs with 0.9 m of freeboard. Recommended average height increases would have been 0.9 m for levees in Corrales and up to 1.2 m in the Belen area. The Albuquerque reach met minimum requirements of protection of 42,000 fs (recurrence frequency of 270 years) and rehabilitation of levees was not recommended (U.S. Army Corps of Engineers 1986).

Effects of the Levee System on the Rio Grande Floodplain Ecology

The environmental effects and benefits created by the levee system and subsequent modifications are varied depending on one's interests. From the COE viewpoint the major effects of levee construction in the Albuquerque area are (1) increased security from flooding for about 285 km^2 of developed floodplain; (2) removal and modification of about 150 ha of riparian vegetation, 15 ha permanently and 134 ha temporarily; (3) a short-term reduction in wildlife habitat use; (4) the potential for marsh development and increased wildlife benefits and recreational use; and (5) ongoing economic benefits. It may not be possible to evaluate the levee system as a discrete factor influencing the floodplain ecosystem.

The levee system is intimately associated with the irrigation system, riverside drains, and effects of flow regulation by dams upstream. Levees certainly prevent flood waters from inundating once natural floodplains (now outside the levee system), thus depriving those areas of needed seasonal waters and sediments. The systems of drains flanking the levees inhibit river waters from entering the floodplain groundwater system,

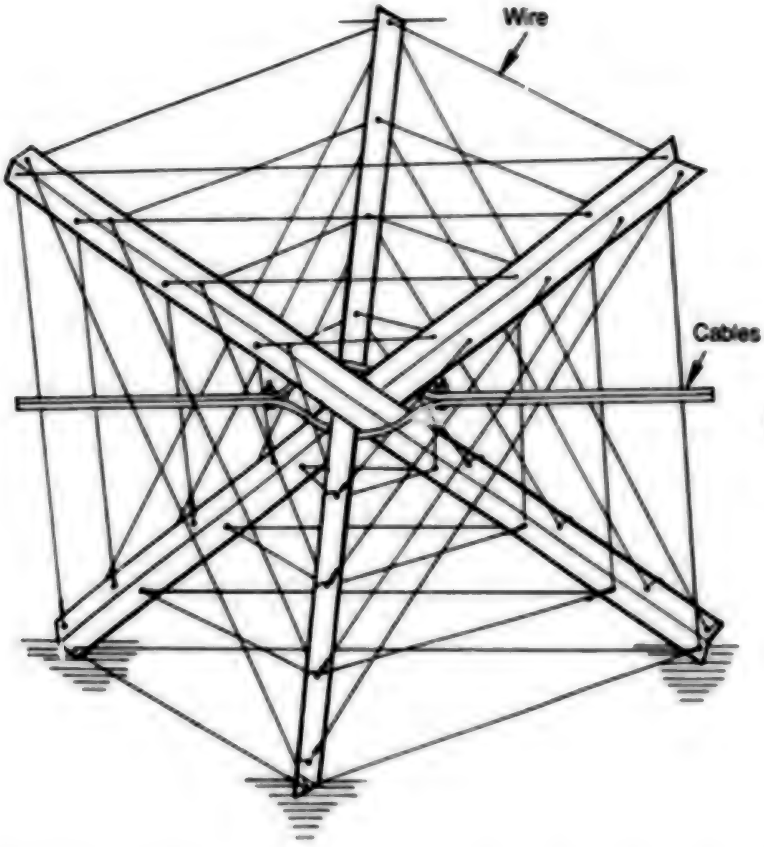

Fig. B-2. Example of single jetty unit, or jack, used on the Middle Rio Grande (U.S. Bureau of Reclamation 1977).

thus creating another unnatural effect on the floodplain system.

Kellner Jetty Fields

Jetty fields are devices that add protection to existing levee systems and help establish channel stability in planform. Along the MRG, Kellner jetty fields abut against the levees; these jetties are designed to protect the levees by retarding flood flows, trapping sediment, and promoting establishment of vegetation, which is important in defining the low-flow channel of the Rio Grande (U.S. Army Corps of Engineers 1986).

A Kellner jetty, or jack, consists of three 10.2-×10.2-×0.64-cm steel angles, 3.6–4.9 m long, placed at right angles to each other (Fig. B-2). The steel angles are bolted together in the center and laced with heavy wire. Jacks are spaced on 3.8-m centers and connected with 1.3- to 1.9-cm-diameter wire ropes.

The connected jetties form what is called a jetty line. Two types of jetty lines are referred to as diversions and retard lines. Diversion lines are jetty lines that are installed parallel to levees, and retard lines connect the diversion line to the levee, or groin (dike), at an angle to the diversion line (U.S. Bureau of Reclamation 1977; Fig. B-3).

The Kellner jetty field is particularly suited for heavily silt-laden streams such as the Rio Grande. The jetty field works as follows:

As the sediment-laden water crosses a jetty line, the velocity is reduced and some of the sediment in suspension is deposited; second, due to a slight amount of backwater created within the field, the water surface within the field becomes slightly higher than that in the floodway channel causing a recirculation of water back into the floodway channel; third, since the concentration of the sediment load has been reduced in the recirculated water, a small amount of sediment is picked up from the river bed. In this manner the river tends to control itself by creating its own banks and scouring its own bed (U.S. Bureau of Reclamation 1977, p. A-16).

Sediment accumulated at the jetties is conducive to establishment of vegetation, which further

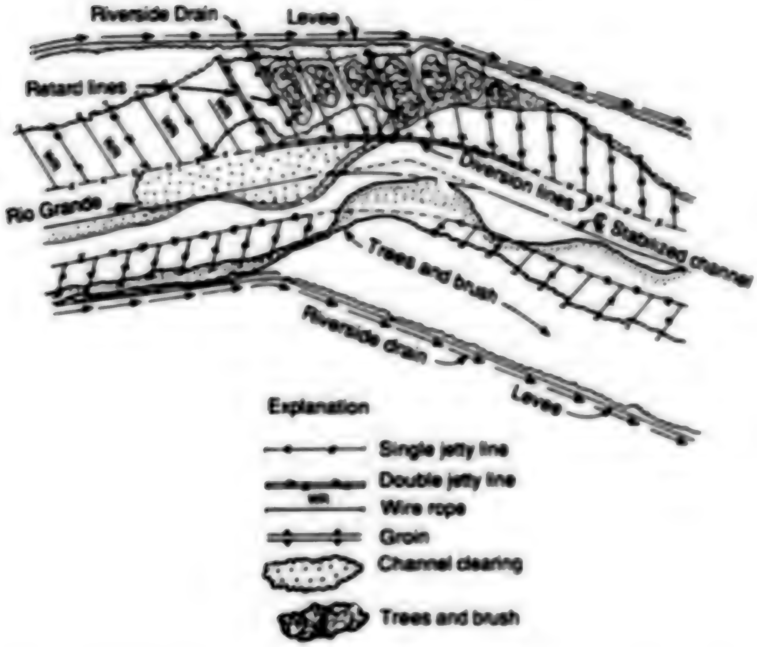

Fig. B-3. Illustration of a typical jetty line on the Middle Rio Grande (U.S. Bureau of Reclamation 1977).

enhances the function of the jetties and rapid growth of vegetation. Within a short period a thick growth of vegetation may be established, which helps stabilize the low flow channel. The system can be readily adapted to provide protection for levees, riverbanks, and bridge abutments (Woodson and Martin 1963).

The existing jetty fields in the reach below Cochiti Dam may now be less effective because of changes in the river since closure of the dam (Lagasse 1981). Kellner jetty fields, which are permeable, are effective only if there is sufficient debris carried by the stream, and the suspended sediment concentration must be large so that there will be deposition in the jetty field.

Studies by Lagasse (1980, 1981) indicated a general tendency toward degradation in the Cochiti to Isleta reach and development of gravel-armored reaches since dam construction. These are strong indicators of a dramatic change in sediment regime below the dam, which creates less favorable conditions for jetty stabilization. Reduced sediment on the main stem, reduced sediment delivery from tributaries such as the Jemez River, and less frequent inundation of the floodplain may diminish the effectiveness of the jetty fields. A degradational environment and reduced sediment supply will induce scour and could undercut jetties such that they fall into the channel; the jetties then are susceptible to burial, which could render the jetty system useless, thereby leaving levees largely unprotected.

Since 1951 the BOR and COE installed in excess of 100,000 individual jetties occupying more than 2,000 ha. The COE presently provides maintenance on the jetties. From 300 to 600 jetties must be replaced on an annual basis because of theft and cable breakage.

Arroyo Flood Control

Flood threats from uncontrolled, ephemeral tributaries to the Rio Grande remain great, especially in and around the Albuquerque and Socorro metropolitan areas. The unique geologic and geomorphologic conditions in the two areas and the dramatic changes in watershed hydrology brought about by urbanization (e.g., removal of natural vegetation, paved roads, parking lots, and houses reduce infiltration and enhance runoff) make these areas highly susceptible to potentially damaging floods such as occurred in July 1988 in the Albu-

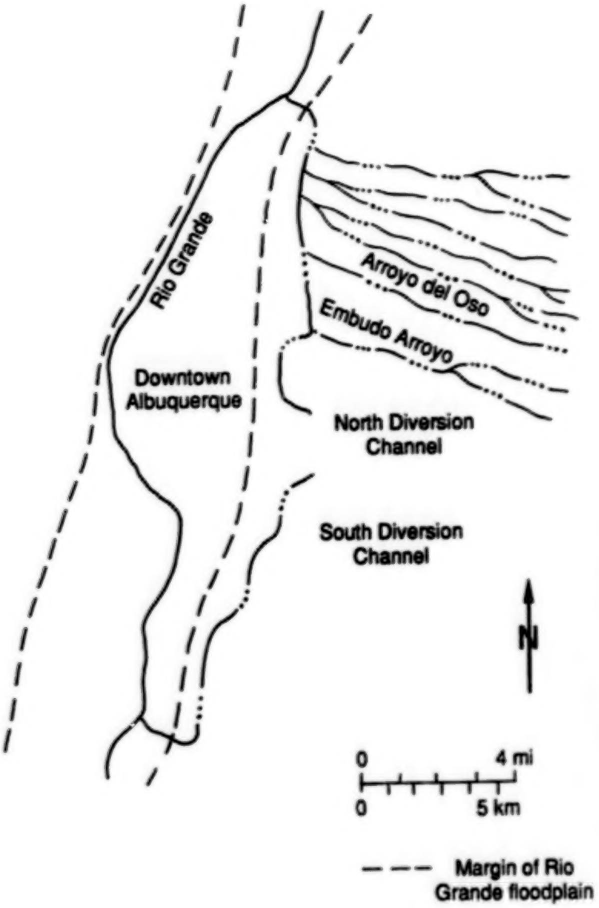

Fig. B-4. Schematic illustration of AMAFCA diversion channels.

querque area. Following several large, damaging floods east of the Rio Grande in Albuquerque in 1955, 1961, and 1963 (U.S. Army Corps of Engineers 1970) the Albuquerque Metropolitan Arroyo Flood Control Authority (AMAFCA) was created to address and attempt to alleviate the problem (Lambert et al. 1982). AMAFCA is responsible for construction and maintenance of the impoundments and arroyos, but routinely contracts with the COE (Albuquerque District) to advise, construct, and maintain the system.

The AMAFCA Flood Control System

The basic flood control system consists of concrete and earthen retention dams in the upper tributary basin regions near the foot of the Sandia Mountains and concrete-lined arroyos that feed to larger channels. These channels ultimately flow into either the North Diversion Channel, which empties into the Rio Grande upstream from Albuquerque north of the Corrales Bridge, or the South Diversion Channel, which empties into the Rio Grande just upstream from Tijeras Creek (Fig. B-4). Most of the time there is no flow in the diversion channels, but the North Diversion Channel has carried flows up to 11,000 cfs.

More problematic are the intense local effects of high intensity precipitation events in small tributary basins. These tributaries can produce extreme local damage when charged with high volumes of sediment and water. For example, the west mesa of Albuquerque has in the past decade experienced rapid urban growth. Locally damaging floods in the past decade have made residents of the west mesa acutely aware of flood potential in this area. Flood control on the west side of the valley has been slower to evolve than on the east side, but flood control is gaining momentum on the west mesa. Large earthen and concrete impoundments and drop structures, designed to attenuate peak discharge and reduce flow velocities, have been constructed in recent years.

Effect of Arroyo Flood Control on the Rio Grande Floodplain Ecology

Because of the nature of storms and floods produced in the tributary basins, the exact effect on the floodplain ecology of the Rio Grande is difficult to evaluate. A major contribution by these ephemeral tributaries and their periodic floods is the large volume of sediment and brief, high discharge.

One effect of arroyo flood control is that floodplains do not receive periodic influxes of sediment and water, lack of which may also affect the plant community along the floodplain. Arroyo flood control also means that urban development may reach into areas that were once subject to flood threat. In the recent past, urban development expanded into potentially flood-prone areas. This was due in part to an insufficient understanding of process geomorphology and concepts of landscape evolution, and inexperience in recognition of subtle landscape expressions that help identify areas prone to flooding. Recently, AMAFCA has begun to recognize the relation between the landscape and urbanization in a semiarid environment, and new zoning ordinances are beginning to affect the location of urban development.

A list of current *Resource Publications* follows.

166. Checklist of Vertebrates of the United States, the U.S. Territories, and Canada, by Richard C. Banks, Roy W. McDiarmid, and Alfred L. Gardner. 1987. 79 pp.
167. Field Guide to Wildlife Diseases. Vol. 1. General Field Procedures and Diseases of Migratory Birds, by Milton Friend, Cynthia J. Laitman, and Randy Stothard Kampen. 1987. 225 pp.
168. Mourning Dove Nesting: Seasonal Patterns and Effects of September Hunting, by Paul H. Geissler, David D. Dolton, Rebecca Field, Richard A. Coon, H. Franklin Percival, Don W. Hayne, Lawrence D. Soileau, Ronnie R. George, James H. Dunks, and S. Dwight Bunnell. 1987. 33 pp.
169. Saltcedar Control for Wildlife Habitat Improvement in the Southwestern United States, by Theodore A. Kerpez and Norman S. Smith. 1987. 16 pp.
170. Pesticide Use and Toxicology in Relation to Wildlife: Organophosphorus and Carbamate Compounds, by Gregory J. Smith. 1987. 171 pp.
171. Sand and Gravel Pits as Fish and Wildlife Habitat in the Southwest, by William J. Matter and R. William Mannan. 1988. 11 pp.
172. Satellite Telemetry: A New Tool for Wildlife Research and Management, by Steven G. Fancy, Larry F. Pank, David C. Douglas, Catherine H. Curby, Gerald W. Garner, Steven C. Amstrup, and Wayne L. Regelin. 1988. 54 pp.
173. Key to Acanthocephala Reported in Waterfowl, by Malcolm E. McDonald. 1988. 45 pp.
174. Obsolete English Names of North American Birds and Their Modern Equivalents, by Richard C. Banks. 1988. 37 pp.
175. Procedures for the Analysis of Band-recovery Data and User Instructions for Program MULT, by Michael J. Conroy, James E. Hines, and Byron K. Williams. 1989. 61 pp.
176. Sago Pondweed (*Potamogeton pectinatus* L.): A Literature Review, by Harold A. Kantrud. 1990. 89 pp.
177. Field Manual for the Investigation of Fish Kills, by Fred P. Meyer and Lee A. Barclay, editors. 1990. 120 pp.
178. Section 404 and Wetland Alterations in the Platte River Basin of Colorado, by Douglas N. Gladwin, Mary E. Jennings, James E. Roelle, and Duane A. Asherin. 1991. 19 pp.

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